

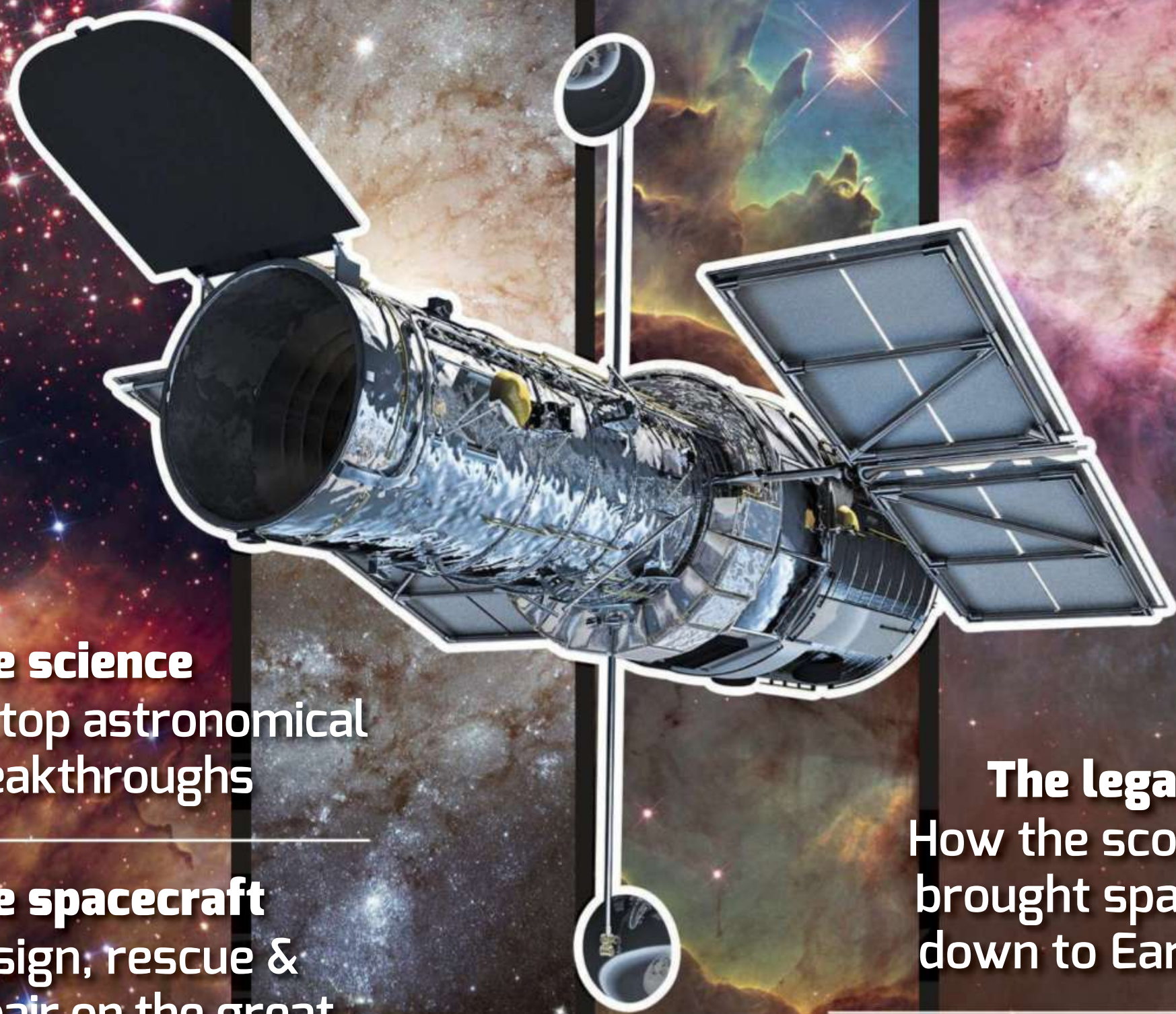
BBC

Sky at Night
MAGAZINE

DISCOVER SPACE
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HUBBLE

30 YEARS OF DISCOVERY



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Its top astronomical
breakthroughs

The spacecraft

Design, rescue &
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The legacy

How the scope
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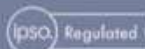
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Welcome



Thirty years ago a spacecraft launched that was to fundamentally change our relationship with space. The Hubble Space Telescope has played a part in many of the defining astronomical discoveries of the last three decades, from the demotion of Pluto to the theorising of dark energy. Yet the power of its imagery has also revealed the Universe to everyone, with a clarity and immediacy matched by nothing before it.

Thanks to Hubble, today we all know what the cosmos looks like. Where earlier ages looked up and pictured God in the stained glass of lofty cathedrals, today we can see the processes of Nature at work, captured by Hubble in the multicoloured wavelengths of light from a star-forming region lightyears across, or the multiple far-off galaxies revealed in the smallest sliver of night sky.

But Hubble's remarkable scientific and cultural body of work almost didn't happen, and the story of its flawed construction, eventual rescue and regular maintenance is as gripping as a soap opera – there's hubris, heartbreak, courage and redemption.

In this special issue we celebrate all of these aspects: the engineers who developed the concept, the astronauts who first fixed then maintained and upgraded Hubble on its high orbital perch, the scientists who used its observational power to make remarkable leaps of understanding, and the impact it has had on wider society. You'll find many of the space telescope's most beautiful images on the following pages too. Enjoy!

Chris Bramley, Editor

Meet the writers

Ben Evans



Ben is the author of several books on the history of spaceflight. On Hubble he says: "I have always

loved adventure stories and Hubble's journey is the ultimate. As it continues to push the limits of knowledge, its discoveries continue to astound me."

Elizabeth Pearson



Elizabeth is *BBC Sky at Night Magazine's* news editor. She says: "The Universe seems unchanging to

humans, so it was amazing to learn how Hubble has seen changes in the cosmos over its 30 years, like the slow expansion of a supernova."

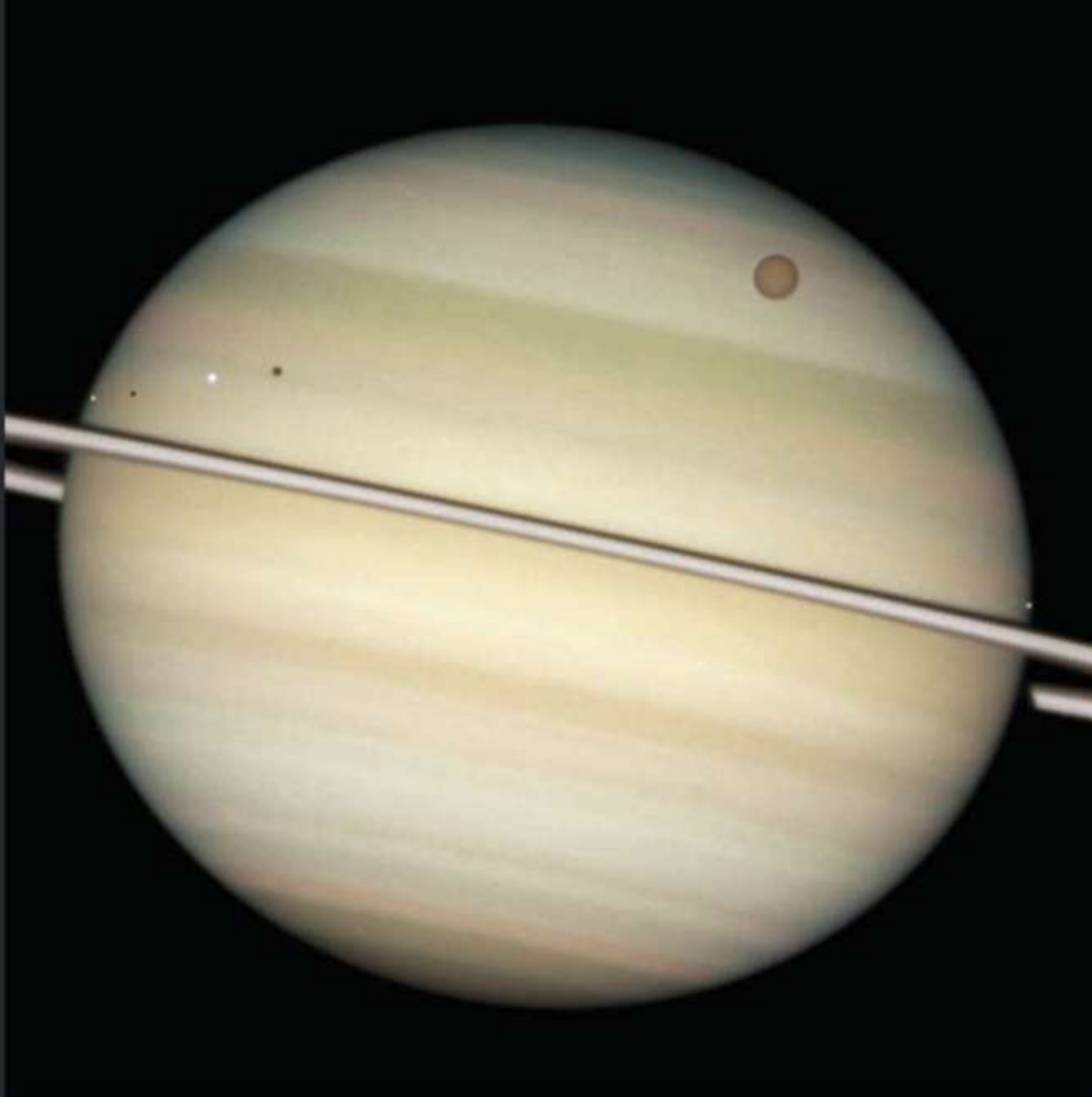
The spiral galaxy M74 in
the constellation Pisces

NASA/ESA AND THE HUBBLE HERITAGE (STSCI/AURA) · ESA/HUBBLE COLLABORATION



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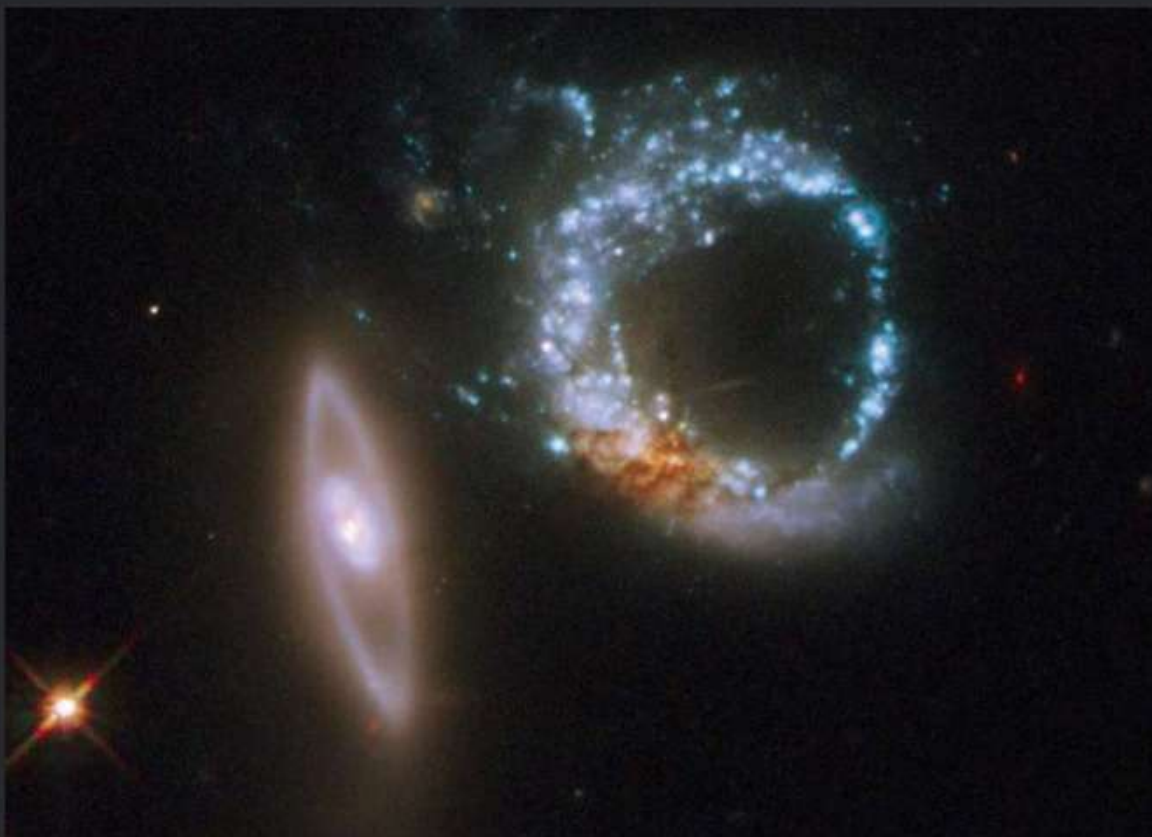
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▲ Lunar transit

CAPTURED: 24 FEBRUARY 2009

Four of Saturn's 82 moons are captured passing in front of their parent planet. Far left are the white icy moons Enceladus and Dione (next to the black dots of their shadows), top right is the large orange moon Titan, and far right is the icy moon Mimas. Saturn moon transits like these are rare to see because they only happen when the plane of the planet's rings is 'edge on' as seen from Earth.



▲ A perfect 10

RELEASED: 30 OCTOBER 2008

These interacting galaxies, together known as Arp 147, appear like the number '10' when viewed from the orientation of Earth. The galaxy on the left is relatively undisturbed, making it look like a clean number '1', while the more messy blue ring of the right-hand galaxy suggests explosive star formation in action.





▲ Fantasia

CAPTURED: 1-2 FEBRUARY 2010

This stunning, whimsical image of the Carina Nebula belies the ferocious star formation brewing in its billowing clouds of gas and dust. Hot, young stars sculpt the clouds with their wild stellar winds and scorching ultraviolet radiation. The image was released to celebrate the 20th anniversary of Hubble's launch.



NASA/ESA/M. ROBERTO (SPACE TELESCOPE SCIENCE INSTITUTE/ESA) AND THE HUBBLE SPACE TELESCOPE
ORION TREASURY PROJECT TEAM, NASA/ESA AND THE HUBBLE HERITAGE TEAM (STSCI/AURA)

◀ Stellar nursery

RELEASED: 11 JANUARY 2006

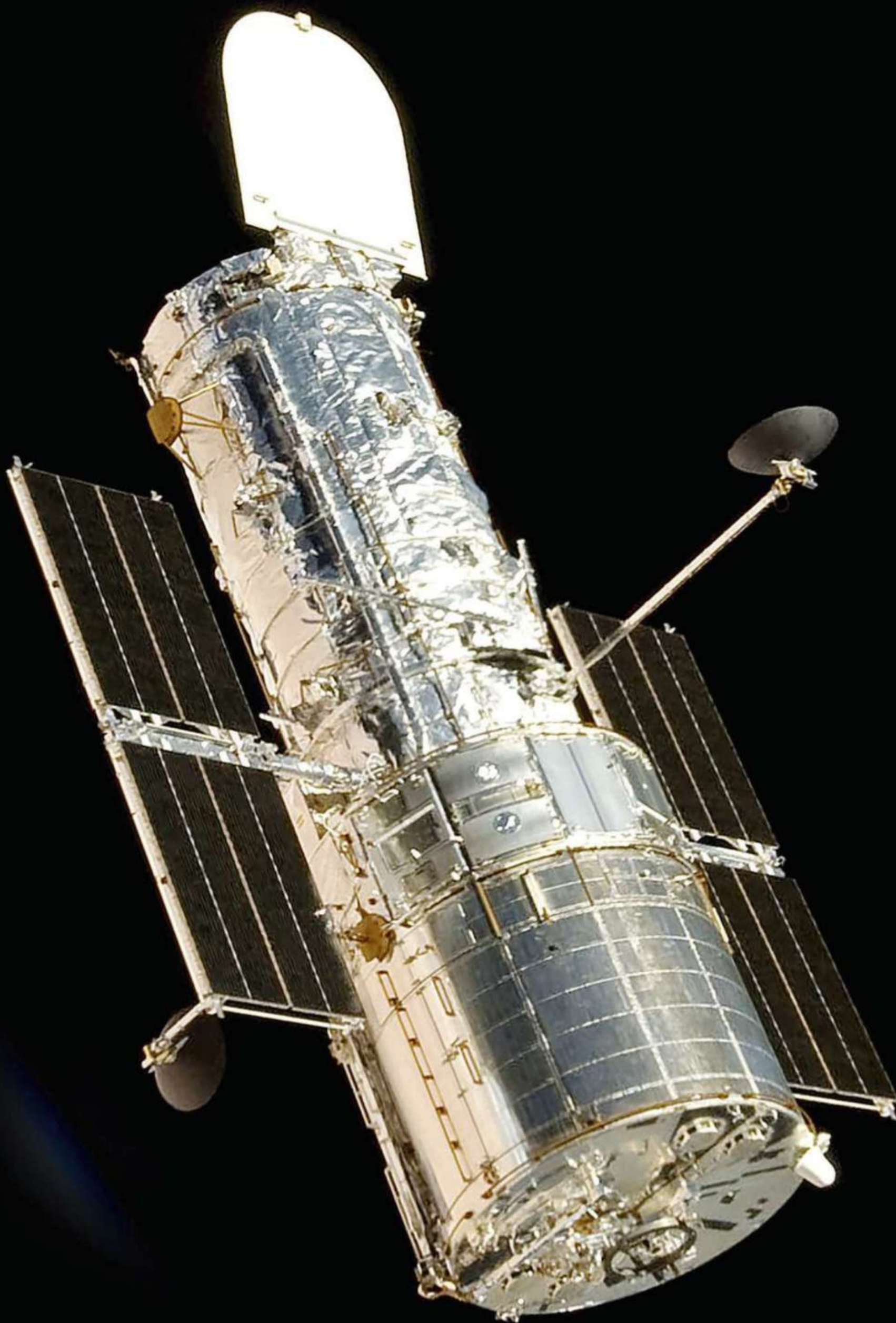
This stunning image offers the sharpest view ever taken of the Orion Nebula (M42), created using 520 different exposures. Stars in the bright central region (the Trapezium) unleash UV light, carving a cavity in the nebula. As M42 is only 1,500 lightyears away, it can be spotted with the naked eye.



▲ Galaxy clash

RELEASED: 20 APRIL 2011

This image of a pair of galaxies, collectively known as Arp 273, was released to celebrate the 21st anniversary of Hubble's launch. Tidal interactions between the two galaxies make them look slightly distorted. It is possible that the smaller galaxy might once have passed through the larger one. Interactive galaxies like these are thought to be fairly common.



NASA/ESA

Hubble drifts over Earth after its
release on 19 May 2009 by the crew
of the Space Shuttle Atlantis



THE SPACECRAFT

Hubble is an icon of space engineering. A first of its kind. A scientific marvel that has punched above its weight. But the planning, construction and launch of the space telescope did not go unhindered – there were many hiccups along the way. Its subsequent success is testament to the ingenuity of its engineers and the bravery of the astronauts who serviced it. From the initial concept to the final design, the well-publicised launch to the risky repair missions, the technological issues to the innovative solutions, this section takes a look at the birth and life of Hubble, and the people behind the scenes who made it a success story.

Planning a telescope in SPACE

The preparation for the Hubble Space Telescope is a story that stretches back through the 20th century

By Ben Evans

Pulitzer prize-winning journalist John Noble Wilford wrote in *The New York Times* in April 1990: "After 45 years of dreaming, the Hubble is ready to be taken into orbit."

As he penned those words, Space Shuttle Discovery stood poised on a Florida launch pad, its payload bay packed with NASA's scientific showpiece: the \$1.5 billion Hubble Space Telescope. Long billed as being able to see further, deeper and older into space than ever before – back to the Universe's infancy, when the earliest stars and galaxies took form, shortly after the Big Bang – Hubble promised

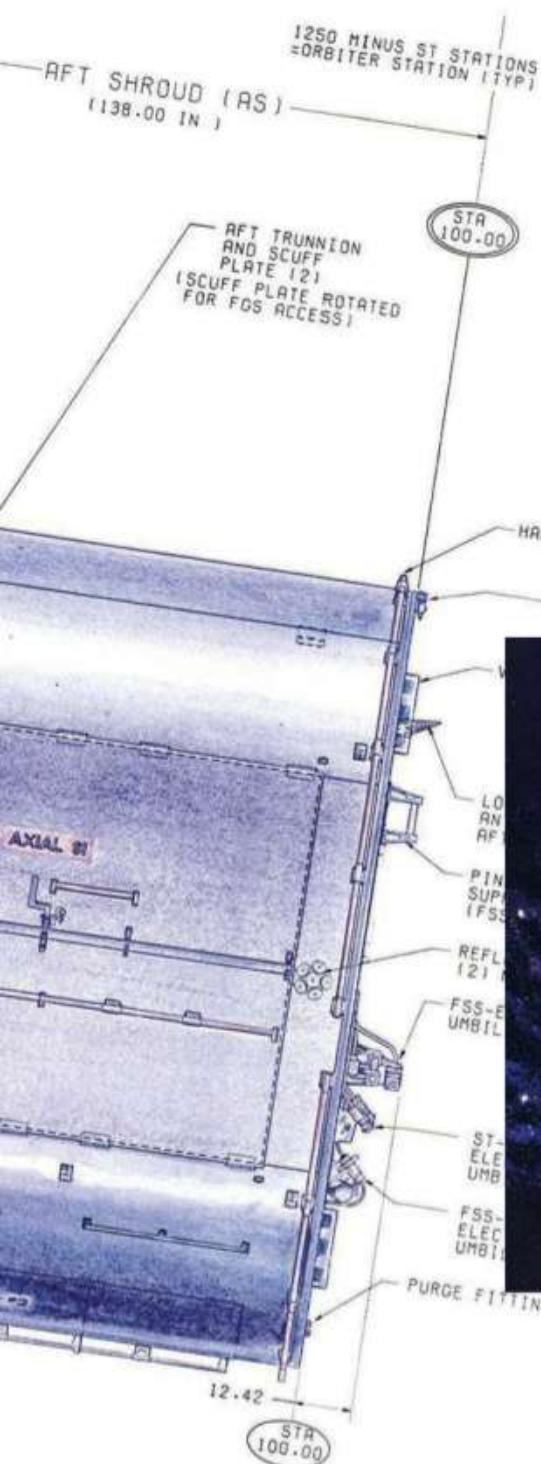
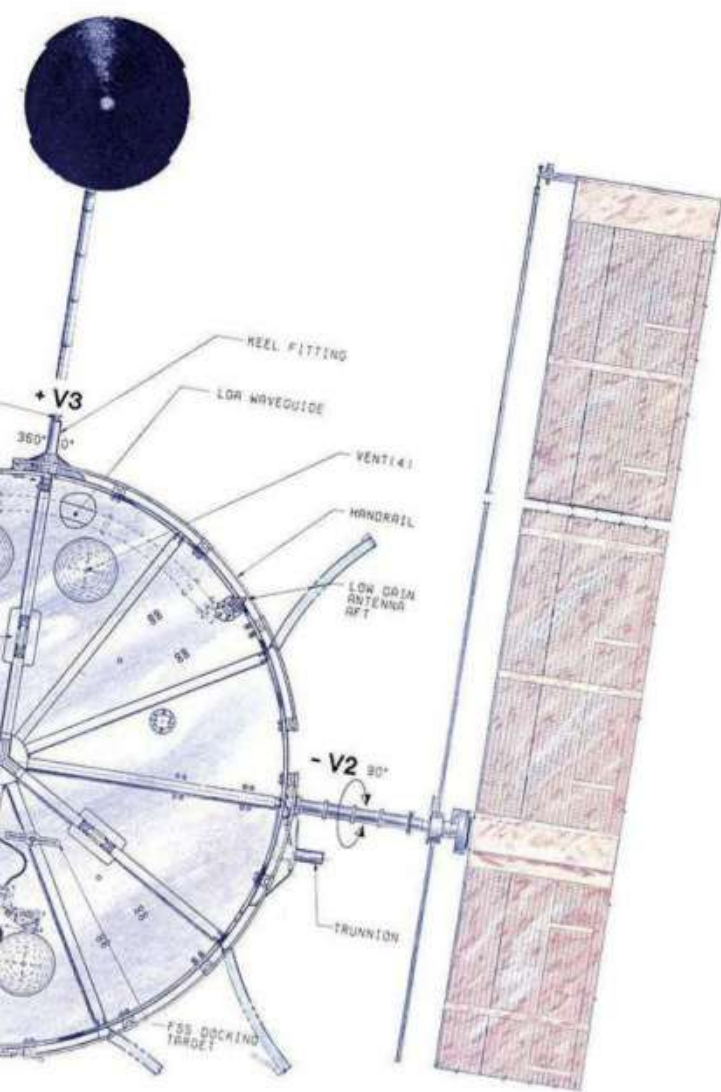
nothing less than an astronomical revolution. And for NASA, it was the eighth wonder of the world.

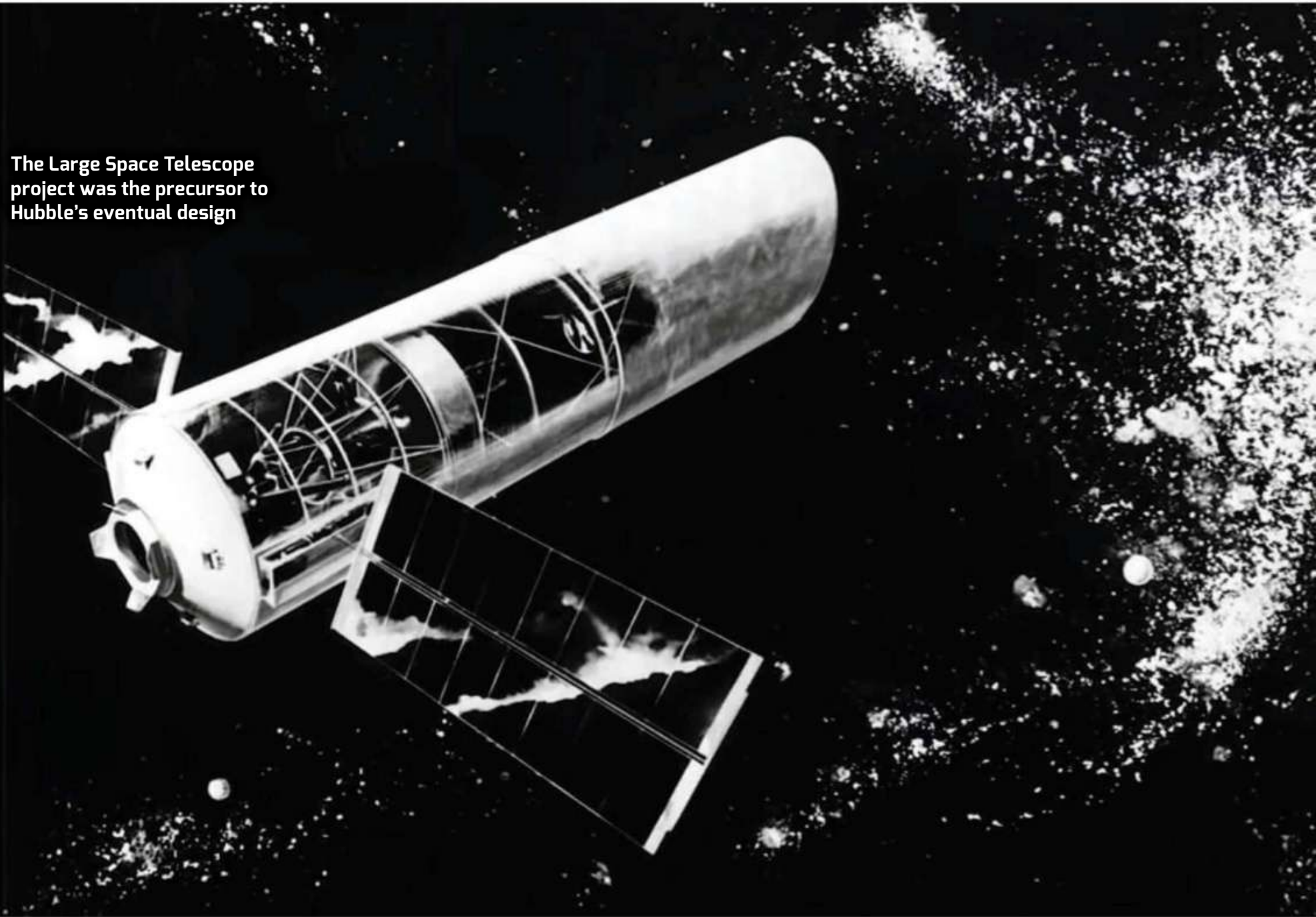
The idea of putting an observatory high above the atmosphere to bring twinkling stars and fuzzy galaxies into sharp focus was not new. Almost a century ago, the German engineer Hermann Oberth wrote about using a rocket to launch a telescope into space and in 1946 the U.S. astronomer Lyman Spitzer showed how such an instrument could easily outmatch any of its ground-based counterparts. Firstly, the effect of atmospheric distortion would be gone, allowing for greater angular resolution and, secondly, the telescope could study the entire electromagnetic spectrum. Not just visible light, but also infrared and ultraviolet radiation (largely absorbed in our atmosphere) could be observed with crystalline clarity.

Early plans

In 1962, the National Academy of Sciences endorsed proposals for an orbiting telescope and Lyman Spitzer was put in charge of the group identifying its scientific goals. A key early task was to show that space-based telescopes could be useful and so, after several early failures, a pair of Orbiting Astronomical Observatories – Stargazer and Copernicus – were

An artist's impression of the Orbiting Astronomical Observatory Stargazer





The Large Space Telescope project was the precursor to Hubble's eventual design

➤ launched in 1968 and 1972. They demonstrated the usefulness of space-based telescopes, revealing comets shrouded in vast halos of gaseous hydrogen, the ultraviolet brightness of distant dying stars, and the discovery of the first long-period pulsars.

Their success convinced NASA to build a large space-based reflecting telescope, initially called LST, whose 3m-wide primary mirror promised to bring even the furthest astronomical objects into stark relief. Spitzer's prominent role made some scientists wonder, only half-smilingly, if the acronym stood for 'Lyman Spitzer Telescope'. But the reality was far more prosaic. LST simply denoted a 'Large Space Telescope', paying homage to its school-bus-sized dimensions, its 11,000kg mass, its huge mirror and its colossal potential for astronomy.

A decade after the idea was proposed, NASA's Marshall Space

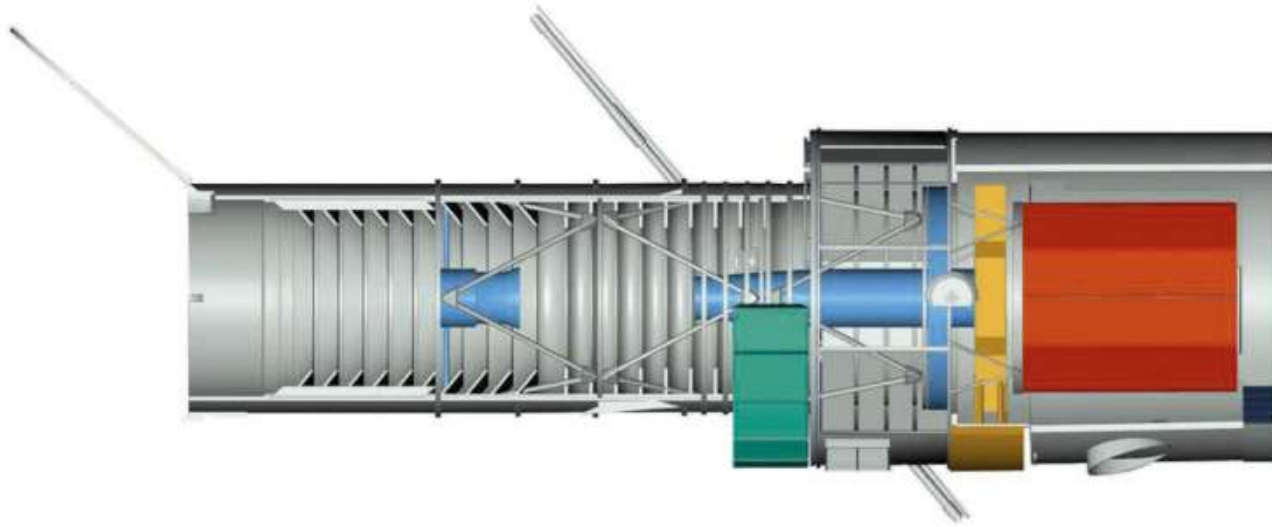
Flight Center in Alabama was chosen to lead the assembly of the LST in 1972, taking responsibility for the spacecraft, its systems and its optical telescope. Goddard Space Flight Center in Maryland would fabricate its scientific instrument package. But to garner support from the astronomical community and Congress, its optical performance had to be kept high and its costs kept low. Those costs skyrocketed to \$700 million, which NASA administrator James Fletcher considered "not conducive" to the fiscally lean years after the Vietnam War. In 1974, the House Appropriations Committee judged LST too expensive, too ambitious and lacking requisite scientific support.

Funding was abruptly withdrawn, but a nationwide letter-writing campaign by astronomers, aerospace contractors and optics firms lobbied exhaustively for its restoration.

Their efforts succeeded, but at the expense of massively downsizing the telescope and requiring NASA to seek international partners. In 1977, the European Space Agency joined the project with a pledge to build its solar arrays and a faint object camera to study the Universe across ultraviolet, visible and mid-infrared wavelengths. In exchange, Europe would receive at least 15 per cent of the telescope's observing time.

Repairs and upgrades

Parallel plans for the Space Shuttle raised the possibility of bringing the telescope home every five years for repairs, then putting it back into space and periodically visiting it for upgrades. Making it 'maintainable' would further offset its enormous cost. And giving the Shuttle a role in the project – which, from 1975, gained the unimaginative moniker of 'Space Telescope' – would



▲ A cross-section of Hubble showing its different sections: axial instrument bay (red), radial instrument bay (yellow), primary and secondary mirrors (blue) and optical instruments (green)

keep it abreast of technological change over 15 years of service. Costs tumbled to \$300 million and in 1978 funding was restored.

The Shuttle's 20m-long payload bay enabled the telescope to evolve into a larger machine, its parts no longer required to fit into tiny volumes, and made assembly, testing and repair correspondingly cheaper. High reliability standards, normally part and parcel of space hardware, were relaxed in response to the promise of regular

Shuttle visits. But the 4.5m width of the payload bay meant the Shuttle could not easily lift a 3m-wide mirror to the required altitude, and so this was reduced to 2.4m. Nevertheless, flying a smaller mirror slashed polishing times from 3.5 years to 2.5 years and cut manufacturing costs. Scientific instruments dropped from seven to four, and its weight fell by a quarter.

In the 1970s, in-space maintenance by astronauts extended little further than replacing photographic film.

"In the 1970s, in-space maintenance by astronauts extended little further than replacing photographic film. Repairing a telescope, on the other hand, demanded six-hour spacewalks and a whole new order of magnitude in terms of risk"

Repairing a telescope, on the other hand, demanded six-hour spacewalks and a whole new order of magnitude in terms of risk. To make it astronaut-friendly, Goddard Space Flight Center's hard-to-access scientific instrument package was replaced by a toroidal 'ring' of equipment bays, wrapped around the telescope's body. This allowed related parts to be grouped together and instruments to be removed and installed easily by astronauts' gloved hands. Foot restraints, handrails and standardised bolts and connectors would further aid spacewalkers as they clambered over the telescope.

Who was Edwin Hubble?



Born in 1889, in Marshfield, Missouri – where a statue of the telescope that bears his name now resides – Edwin Powell Hubble was the son of an insurance executive. A fine athlete and sportsman, he studied law as a pledge to his father, before returning to his boyhood love of astronomy and a doctorate in 1917.

Hubble was an army officer in the First World War and an astronomer at California's Mount Wilson Observatory until the end of his life. Married for 30 years to Grace, his work completely overturned the view at the time that the Universe consisted entirely of the Milky Way. He made this breakthrough by

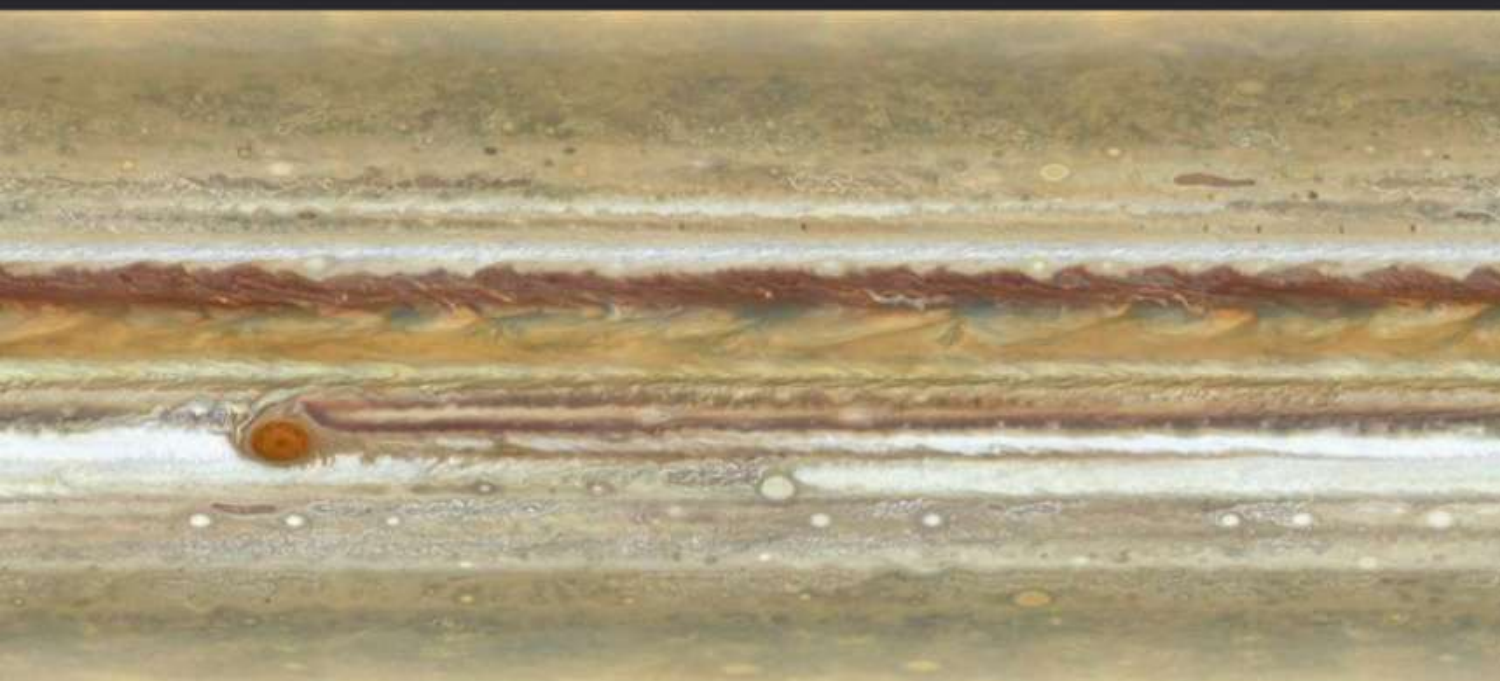
showing that Cepheid variable stars could be used as yardsticks to measure celestial distances, and finding several spiral nebulae too far distant to be part of our galaxy. This discovery totally changed our awareness of the cosmos.

Hubble devised a classification scheme for galaxies and, in 1929, helped validate theories that the Universe expands at a uniform rate. Hubble showed that the further apart galaxies are, the faster they recess from one another. Honoured with an asteroid, a crater on the Moon and a stretch of interstate passing through his birthplace, Hubble is today revered as one of the world's foremost astronomers, whose discovery changed the cosmological view as much as that of Copernicus.

Realistic expectations

By this time, launch had slipped from 1979 to 1983. But even when the Shuttle finally began flying, it was obvious that it could not meet the weekly launch schedules advertised by NASA and the plan to return the telescope to Earth for repairs was scrapped. Some also feared it might get contaminated during its time on the ground, while others felt the expense of re-launching it might see it inauspiciously end its days in a museum. Instead, it would be completely overhauled in space every few years, which meant that greater 'maintainability' had to be built into systems that were never meant to be maintainable.

Even as the telescope weaved its way along a thorny path to space, another issue still lay unresolved. This one-of-a-kind observatory needed a proper name and, in 1983, two decades after proposals for an orbiting telescope were first endorsed, it got one – the Hubble Space Telescope had been christened.



◀ Stormy weather

CAPTURED: 27 JUNE 2019

Distinct bands of roiling clouds rumble across Jupiter in this stretched-out map of the entire planet (excluding the polar regions). The image was created from several exposures taken by Hubble's Wide Field Camera 3 (WFC 3).



◀ In a whirl

CAPTURED: JANUARY 2005

This image of the Whirlpool Galaxy (M51) is a perfect example of a classic spiral galaxy – graceful arms, which are home to young stars, curl in towards the central core, where older stars reside. The smaller galaxy NGC 5195 (right) has been gliding past the Whirlpool for hundreds of millions of years.

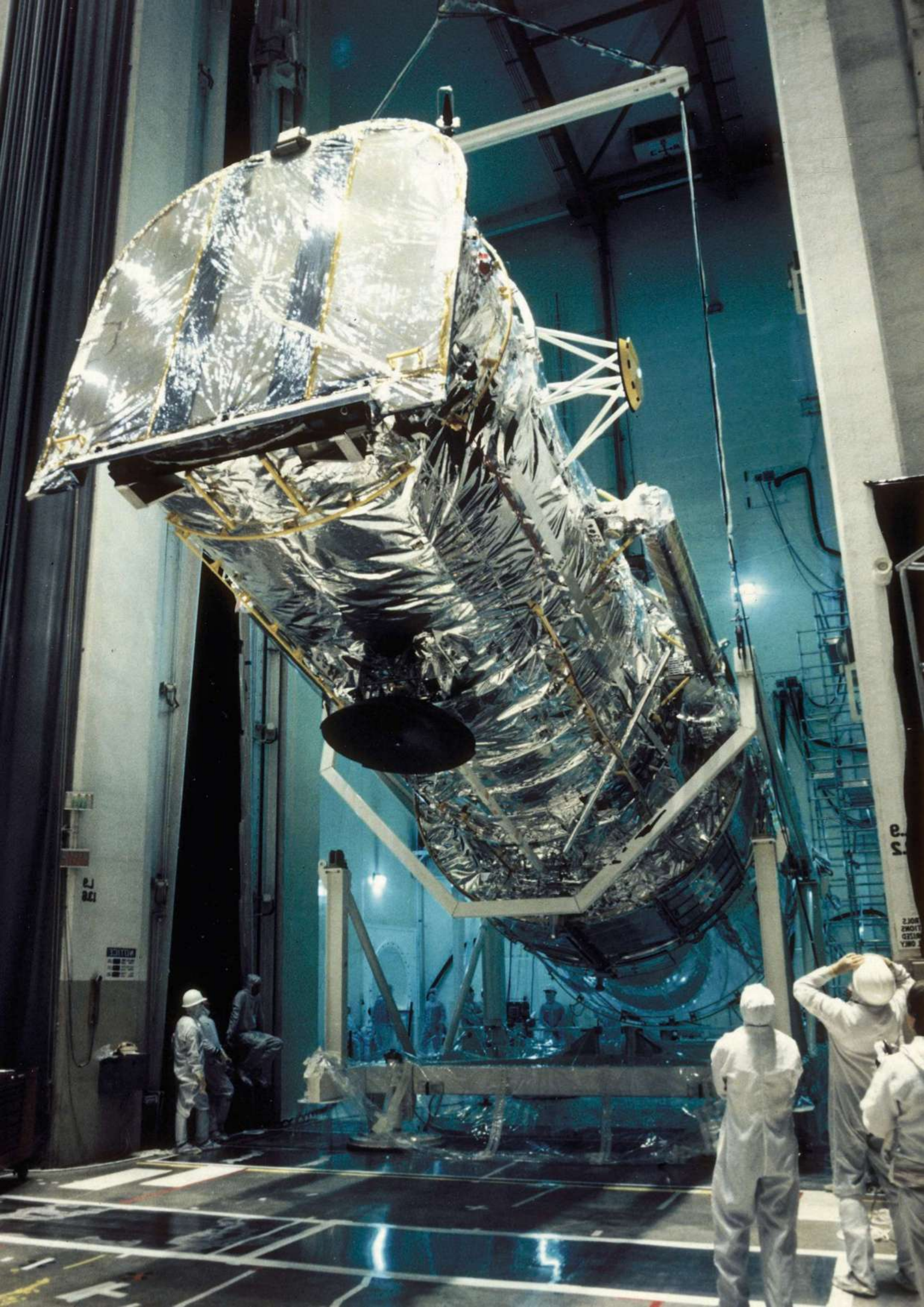
NASA/ESA/S. BECKWITH (STSCI) AND THE HUBBLE HERITAGE TEAM (STSCI/AURA), NASA/ESA/A. SIMON (GODDARD SPACE FLIGHT CENTER), AND M.H. WONG (UNIVERSITY OF CALIFORNIA/BERKELEY), NASA/ESA AND THE HUBBLE SM4 ERO TEAM

Metamorphosis ▶

CAPTURED: 27 JULY 2009

Nicknamed the Butterfly Nebula (or Bug Nebula), NGC 6302 lies within the Milky Way, roughly 3,800 lightyears away. What appear to be delicate butterfly wings are in fact super-heated cauldrons of gas, tearing through space at 950,000km/h. And at the centre sits a dying star that was once about five times the mass of the Sun.





◀ Hubble was built with many layers of insulation to ensure the instruments remained around room temperature

A troubled childhood

Construction of the telescope was an international undertaking of great complexity. Budget pressure was felt all through this phase and would come home to roost with a critical flaw

By Ben Evans

As Hubble took shape in factories and laboratories across the United States and Europe in the late 1970s and early 1980s, its components were being readied to answer some of the thorniest questions in astronomy. These questions lay at the ragged edge of human consciousness: when was the Universe born? How did the earliest stars and galaxies burst into life? And how did the cosmos continuously expand at a uniform rate – as shown by Edwin Hubble himself?

The telescope itself was of a Ritchey-Chrétien design, its primary and secondary mirrors capable of eliminating optical effects with an imaging performance seven to 10 times better than ground-based instruments. But it also proved notoriously difficult

to build and therein lay a festering problem, which would return to haunt Hubble in later life.

Led by NASA's Marshall Space Flight Center in Alabama, the telescope's funding fell precipitously in the early 1970s, to such an extent that its complement of scientific instruments was cut from seven to four. The European Space Agency came aboard as a welcome international partner, pledging a fifth instrument, while British Aerospace in Bristol built a pair of power-generating solar arrays.

In 1977, California-based aerospace giant Lockheed was chosen to assemble this cylindrical behemoth of a spacecraft. At 13 metres in length and the weight of two full-grown elephants, the spacecraft housed the telescope and instruments, guarding them against sweeping thermal extremes ranging from 100°C to -250°C as

Hubble moved from direct sunlight into Earth's shadow during each 96-minute orbit. Shiny multi-layered insulation kept internal temperatures near room temperature, while an aluminium and graphite-epoxy framework accommodated a pointing system of gyroscopes, star trackers and reaction wheels to firmly align the instruments, and precisely aim them at their celestial targets to within 0.007 arcseconds for up to 24 hours at a time.

A complex job

Assembling this masterpiece was an exercise of such complexity that one engineer wryly wondered if the telescope should be made from 'unobtainium'. And although Lockheed had prior expertise making KH-9 spy satellites, it had never built a large orbiting scientific observatory. Moreover, the wholesale cost-cutting ↘



A custom-made, computer-controlled machine polishes the 2.4m-wide primary mirror in 1979, a decade before its tiny flaw was discovered

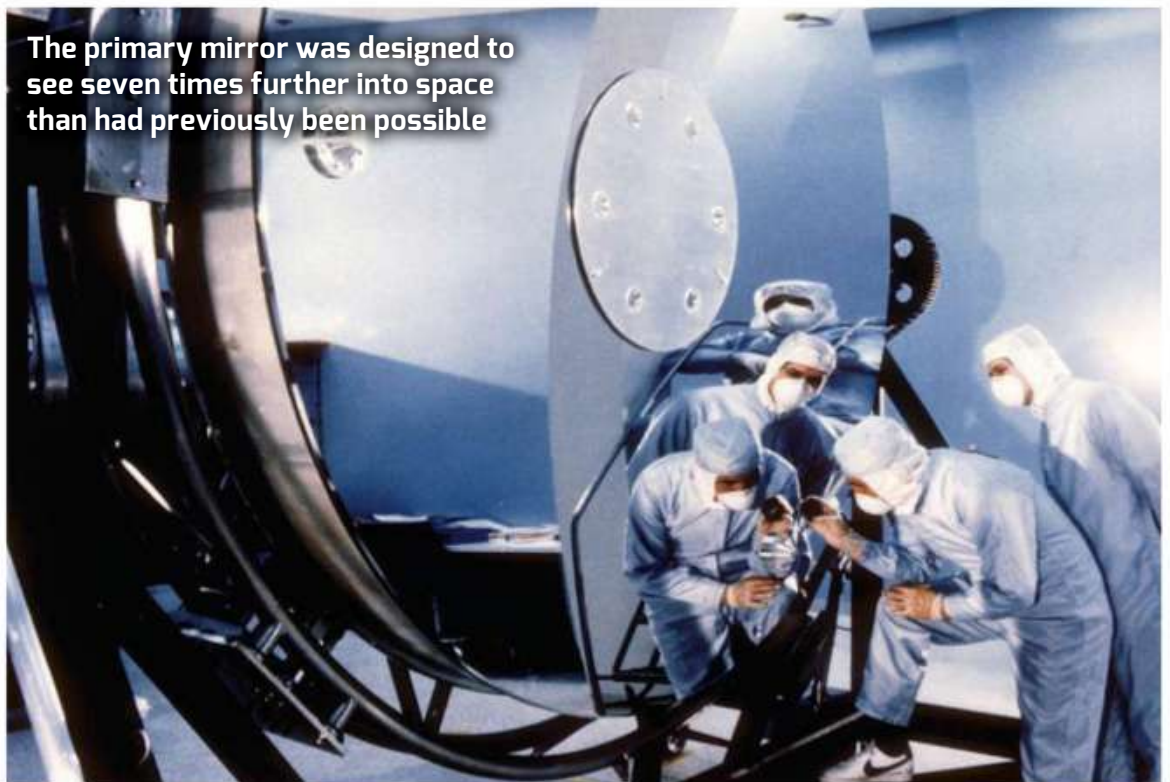
of the previous decade had gone deep and its undesired effects now came home to roost.

Two optics houses, Eastman Kodak – partnered with defence contractor Itek – and Massachusetts-based Perkin-Elmer competed to build the mirrors. Kodak-Itek's \$99.8 million proposal included two independent checks of the grinding and polishing accuracy on the finished optics; by contrast, Perkin-Elmer's \$64.2 million bid offered no such safety net. In 1979, the lowest bid won the contract. It was a decision that would not go unnoticed a decade later, when Hubble's first light revealed critically flawed optics and investigators dug into the root cause of this spherical aberration.

Cutting corners

Right from the start, NASA had serious concerns about Perkin-Elmer. The firm intended to use a custom-made, computer-controlled and untried polishing machine for the mirrors. Hedging its bets against a likelihood of problems, NASA insisted the machine

The primary mirror was designed to see seven times further into space than had previously been possible



first be tested on a smaller mirror and required Perkin-Elmer to subcontract to Kodak-Itek to build a backup mirror with traditional polishing techniques. But worries about the lack of end-to-end testing, sloppiness and poor management remained. One damning NASA report branded Perkin-Elmer's

technical approach as disorganised, ill-disciplined and unsuited to such a high-profile government contract. Lockheed also took sharp criticism for its over-reliance on NASA directives and lack of engineering initiative.

The 2.4m primary mirror – the largest ever put into space – was composed

“At the time of the Challenger disaster, Hubble’s price had swollen to \$1.1 billion”

of ultra-low-expansion glass and took two years to build and polish. Finished in 1981, it was washed in hot, deionised water and coated with protective magnesium fluoride. But as delays continued to plague Lockheed and Perkin-Elmer, and as costs soared, the launch inevitably slipped, eventually settling on October 1986. At the time of the Challenger disaster, Hubble’s price had swollen to \$1.1 billion.

High-spec tech

Meanwhile, deployment tests on the 12m-long solar arrays began in 1981. The arrays resembled enormous roller blinds, to be unfolded in space; their flimsiness dictated by available solar cell technologies and a requirement to be as big as possible to meet Hubble’s four-kilowatt electrical demands. Power from their 48,000 solar cells would be stored in six nickel-hydrogen batteries to feed its instruments and subsystems.

At the telescope’s heart, the primary mirror reflected incoming light from celestial sources onto the 33cm secondary mirror. From there, the beam narrowed, intensified and was routed into the focal plane where the five instruments were situated. And those instruments, built by an international consortium of industry, government and academia, promised to rewrite the astronomy textbooks.

California’s Jet Propulsion Laboratory provided a Wide Field Planetary



The 12m-long solar arrays undergoing deployment tests

Anatomy of a space telescope

At 13 metres in length and as heavy as two full-grown elephants, the Hubble Space Telescope is a complex machine that houses multiple systems



KEY

Original instrument

First replacement

Second replacement

1. Primary mirror
2.4m Ritchey-Chrétien reflector

2. Secondary mirror
33cm secondary mirror

3. Aperture door
Protects Hubble's optics and can be closed if necessary

4. Soft Capture Mechanism
Added in 2009, the SCM will support a robotic spacecraft to deorbit Hubble in the future

5. Solar arrays
Original solar arrays: launched with Hubble in 1990, 12m long, silicon solar cells, flexible
Replacement solar arrays: installed in 1993, identical to original arrays, but with thermal insulation 'sleeves' and springs

to minimise wobbling effect, flexible
Current solar arrays: installed in 2002, 7m long, gallium arsenide solar cells, rigid

6. Pointing systems
Fine Guidance Sensors x3: two are used to point Hubble, and a third supports positioning measurements

7. Gyroscopes x6: used for maintaining Hubble's orientation (hidden on illustration)

8. Wide Field and Planetary Camera (WFPC): launched on Hubble in 1990
Wide Field and Planetary Camera 2: replaced WFPC in 1993
Wide Field Camera 3: replaced WFPC 2 in 2009

9. High Speed Photometer (HSP): launched on Hubble in 1990

Corrective Optics Space Telescope Axial Replacement (COSTAR): replaced HSP in 1993

Cosmic Origins Spectrograph (COS): replaced COSTAR in 2009

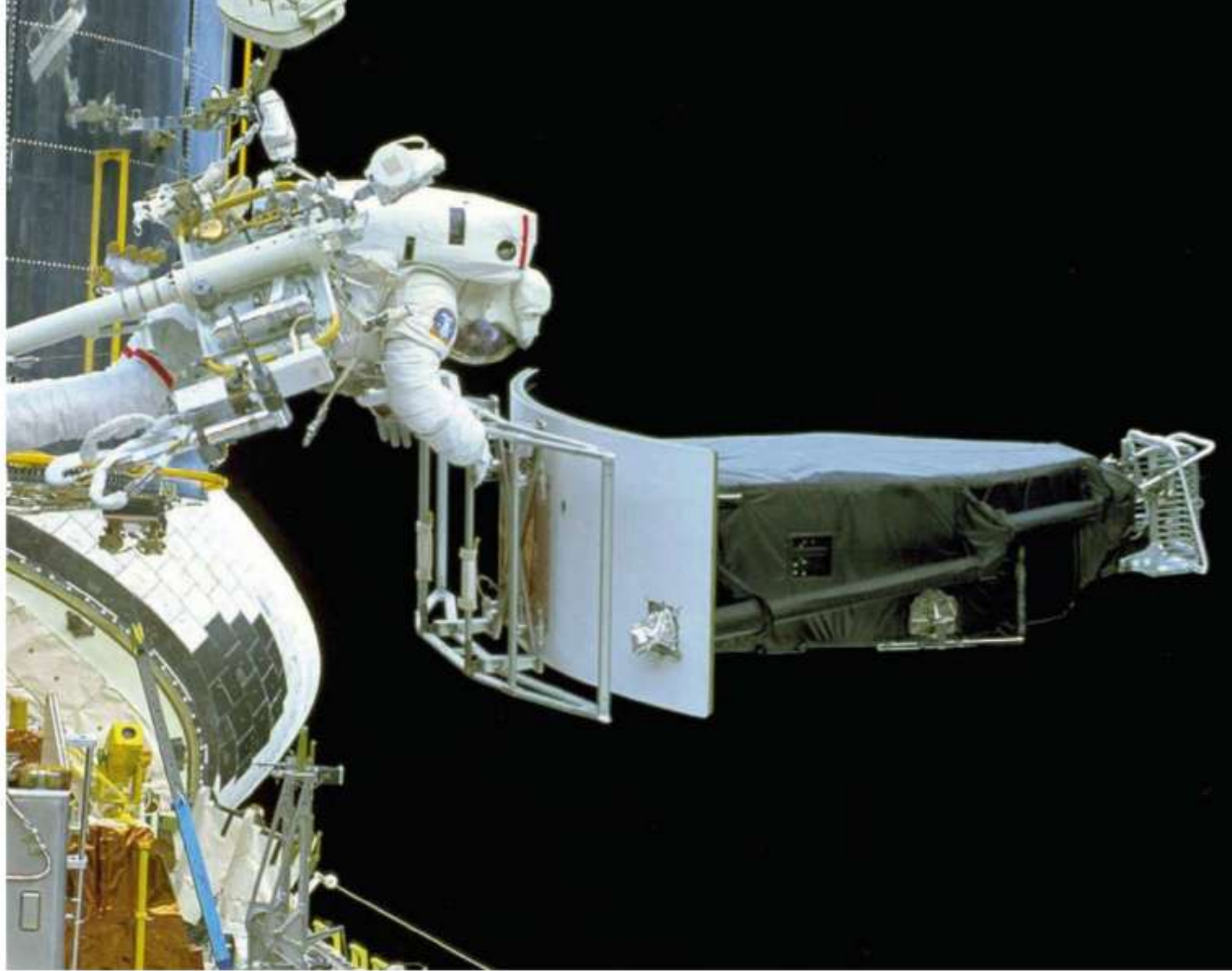
10. Goddard High Resolution Spectrograph (GHRS): launched on Hubble in 1990

Space Telescope Imaging Spectrograph (STIS): replaced GHRS in 1997

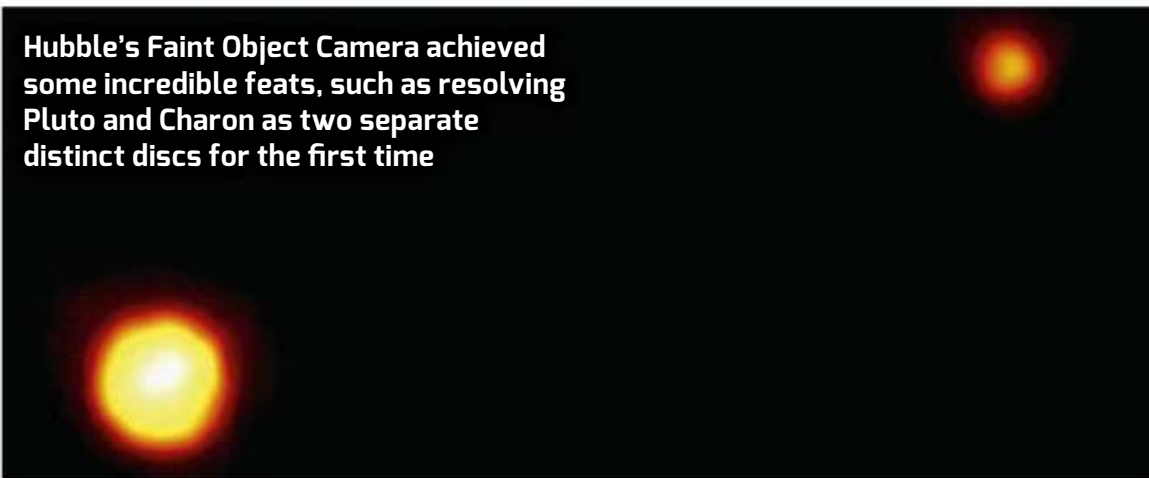
11. Faint Object Spectrograph (FOS): launched on Hubble in 1990
Near Infrared Camera and Multi-Object Spectrometer (NICMOS): replaced FOS in 1997

12. Faint Objects Camera (FOC): launched on Hubble in 1990
Advanced Camera for Surveys (ACS): replaced FOC in 2002

► The first Wide Field Planetary Camera was replaced during a service mission in 1993



Hubble's Faint Object Camera achieved some incredible feats, such as resolving Pluto and Charon as two separate distinct discs for the first time



Madison, was intended to examine the brightness and polarity of distant objects at ultraviolet, visible and near-infrared wavelengths – in the hope that it might pinpoint the locations of suspected black holes. But Hubble's flawed optics rendered HSP virtually useless and it was the first instrument to be decommissioned.

A huge endeavour

By contrast, Europe's Faint Object Camera (FOC), built in Germany by Dornier, enjoyed the longest career of the 'original five' instruments. Its two high-resolution cameras observed ultraviolet and visible light and could distinguish between objects just 0.05 arcseconds apart, promising to yield Hubble's sharpest images, particularly of binary stars. FOC would investigate the cosmological scale of the Universe, looking into distant globular star clusters and observing phenomena fainter than could be seen from the ground.

Back on Earth, when the data streamed in, the scientists would be ready. At the Goddard Space Flight Center, a control station would directly communicate with Hubble via NASA's orbiting network of tracking and data-relay satellites. And on the Maryland campus of the Johns Hopkins University, a dedicated Space Telescope Science Institute (STScI) would run day-to-day operations, selecting astronomical targets and planning an estimated 30,000 observations every year. It was truly a gargantuan endeavour.



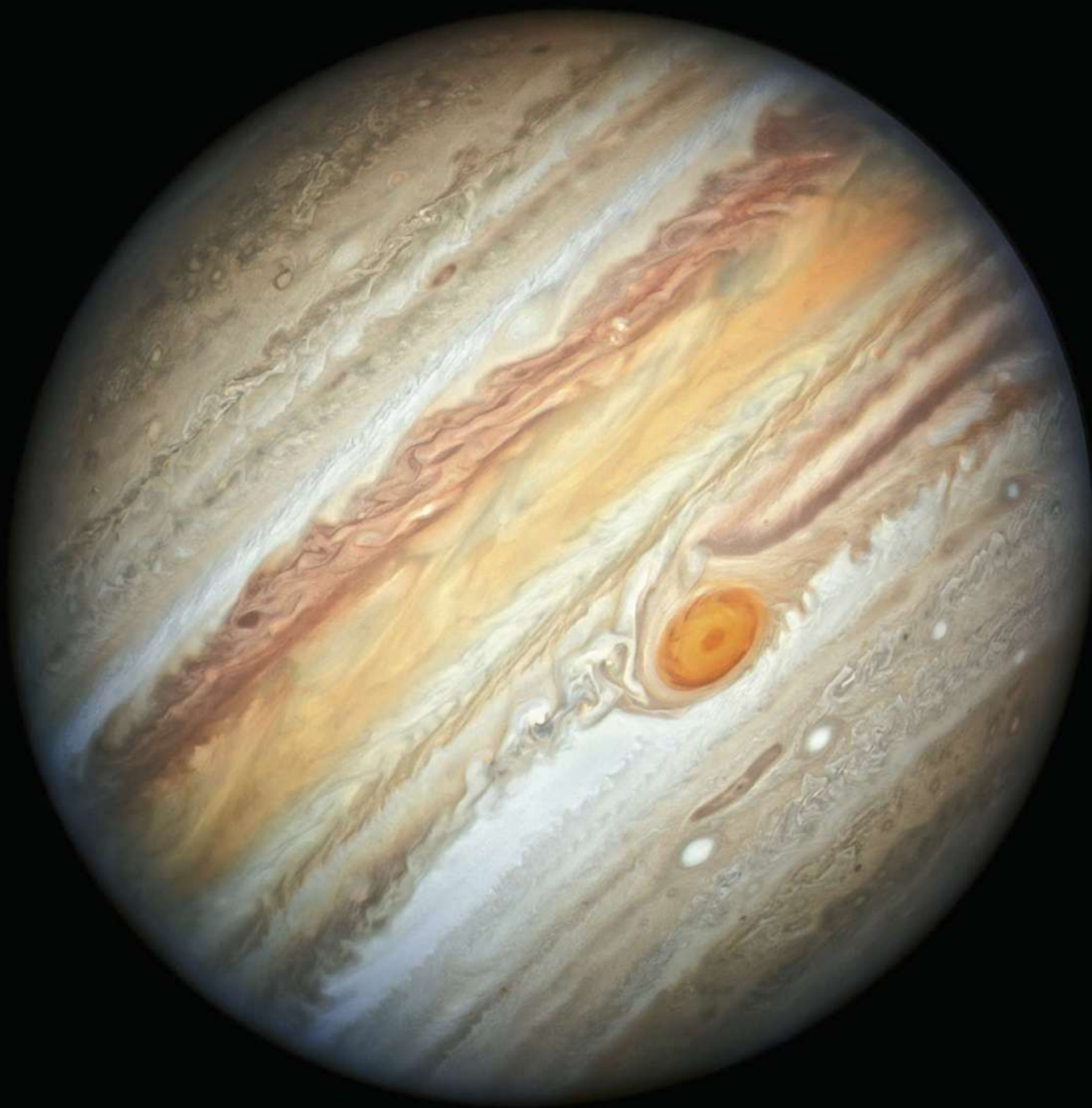
An illustration showing the exchange of information via Hubble, Tracking and Data Relay Satellites and ground stations

Camera (WFPC), whose dual cameras spanned from far ultraviolet to near-infrared wavelengths. It could do panoramic observations of hundreds of distant galaxies and high-resolution imaging of every planet in our Solar System, except Mercury, which lay too near the Sun to be resolvable.

A pair of spectrographs – the Faint Object Spectrograph (FOS), built by the

University of California at San Diego, and the Goddard High Resolution Spectrograph (GHRS) from NASA's Goddard Space Flight Center – would chemically analyse comets, planetary atmospheres, quasars and far-off galaxies in visible and ultraviolet light.

When it was developed, the High Speed Photometer (HSP), built by the University of Wisconsin at



▲ Jupiter: the gas giant in all its glory

CAPTURED: 27 JUNE 2019

The planet's trademark Great Red Spot is a huge storm that is rolling anti-clockwise around the planet, travelling in the opposite direction to the bands of cloud surrounding it. The storm has raged on Jupiter's surface for at least 150 years. It is currently roughly the diameter of Earth, but is shrinking in size – no-one knows what is causing this. The smaller white or brown ovals are much smaller storms that can last for a matter of hours or go on for centuries.



NASA/ESA/A. SIMON (GODDARD SPACE FLIGHT CENTER) AND M.H. WONG (UNIVERSITY OF CALIFORNIA/BERKELEY), ESA/HUBBLE AND NASA, NASA/ESA AND THE HUBBLE HERITAGE TEAM (AURA/STSC)

▲ Mistaken identity

RELEASED: 7 JUNE 2010

Nebula HD 44179 was initially nicknamed the Red Rectangle, because that's what it looked like in early images from Earth. But later shots show it is actually shaped more like an 'X' if viewed from space. It's an unusual example of a protoplanetary nebula, where an old red giant expels its outer layers to expose a hot inner core that radiates UV, which causes the surrounding gas to glow.

Celestial seahorse ►

RELEASED: 19 APRIL 2013

The Horsehead Nebula rises like an enormous seahorse out of roiling waves of gas and dust. This image reveals the nebula in infrared light, piercing through the dusty material that normally obscures its inner regions. The result is a rather ethereal and fragile-looking structure, made of delicate folds of gas – very different to the nebula's appearance in visible light.



A photograph of the Space Shuttle Discovery during its ascent. The shuttle is angled upwards, leaving a massive, billowing plume of white smoke and orange fire from its engines. The background is a clear blue sky. The shuttle itself is a small silhouette against the bright exhaust.

Space Shuttle Discovery lifts off from NASA's Kennedy Space Center on 24 April 1990, carrying a crew of five and Hubble

A precision LIFT-OFF

By Ben Evans

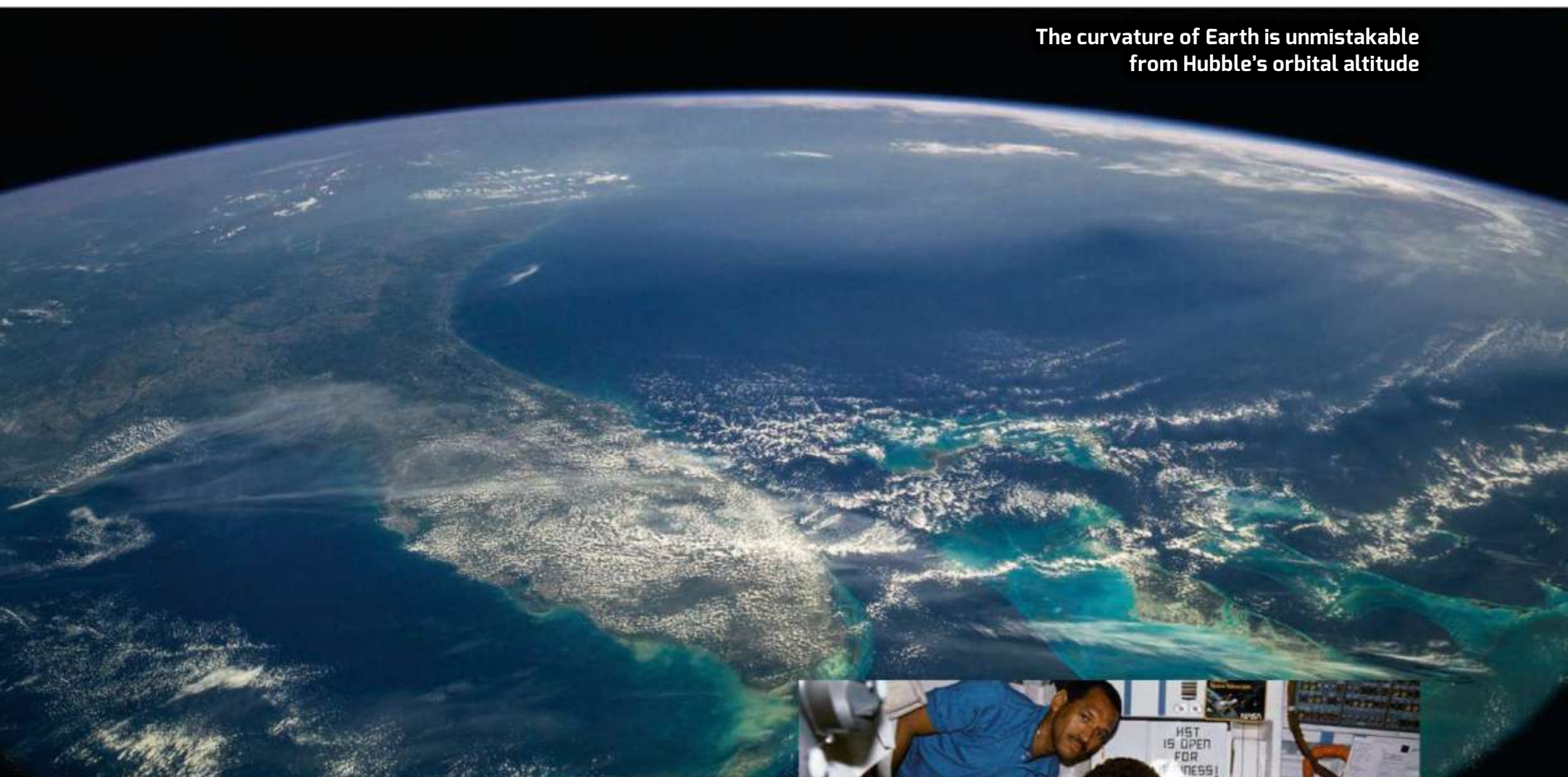
Think the Hubble Space Telescope is a short joyride from the International Space Station? Movies like *Gravity* might confidently assure us that jetpack-wearing astronauts can easily hop between them, but the reality is less straightforward. Firstly, Hubble resides over 550km above Earth, much higher than the station's 400km. And more significantly, the inclination (or 'tilt') of their respective orbital planes – 28.5° for the telescope, 51.6° for the station – makes it far too costly in terms of energy expenditure to travel from one to the other.

Hubble's lofty perch was chosen to meet fuel, performance and safety margins on the Space Shuttle, balanced against the size and mass of the telescope itself. This stout silver monolith had to fly high enough to mitigate the effects of atmospheric drag while maintaining its uninterrupted view of the Universe.

When astronauts John Young, Charlie Bolden, Bruce McCandless, Steve Hawley and Kathy Sullivan were assigned to Shuttle mission STS-61J in 1985, they expected to launch Hubble the following year. The presence of Young – NASA's senior astronaut and veteran Apollo moonwalker – underscored the importance of what Bolden later described as, "...one monster flight". Hawley would deploy the telescope with the Shuttle's robot arm, while McCandless and Sullivan had worked to develop tools and

For Hubble's launch, its orbital path was carefully chosen to account for Earth's gravitational pull and maintenance missions. But nerves of steel were needed to get there and back safely

The curvature of Earth is unmistakable from Hubble's orbital altitude



methods to service it. On the mission itself, those skills would come within a whisker of being needed for real.

Hubble virtually filled the Shuttle's payload bay, imposing tight weight and performance limitations. The telescope's low-impulse control system (and lack of engines) meant the Shuttle had to lift it directly as high as possible into a low-density region of space to reduce the gravitational forces its gyroscopes needed to work against.

A balancing act

Had it flown in 1986, Hubble would have entered space during a 'minimum' period of solar activity, when the Sun's effect on our planet is relatively benign. Young's crew could have put it into an orbit that was high enough to begin its mission and low enough for the Shuttle to conserve fuel. But the loss of Challenger meant it was 1990 before Hubble found itself loaded aboard Shuttle Discovery for liftoff. By then, astronaut Loren Shriver had replaced Young as commander and the flight was renumbered STS-31.

Solar output had also intensified as the increasingly energetic Sun moved towards 'solar maximum' in its 11-year

► The crew of STS-31 – clockwise from top left: Charles F. Bolden, Kathryn D. Sullivan, Steven A. Hawley, Bruce McCandless II and mission commander Loren J. Shriver



cycle of activity. At the altitudes being considered for Hubble this caused atmospheric densities to increase by a factor of up to 15, and operating in high-density regions would make the telescope harder to control, its orbit at risk of decaying more quickly. It also had implications for the first Shuttle servicing mission, STS-61. Hubble's orbit had to naturally decay for the STS-61 crew to reach it without compromising their fuel supply, but if its altitude dropped too much its gyroscopes would become saturated.

A delicate balance, therefore, had to be struck. Determining 'how high' Hubble could fly required accurate forecasting of the intensity of solar maximum, careful observations of orbital decay rates in existing satellites and precise calculations of how

efficiently real Shuttle crews used their fuel. NASA concluded that Hubble could be deployed at an altitude of 612km, higher than any previous Shuttle had ever reached.

Touch and go

This would give the STS-31 crew a splendid view of Earth, its curvature readily apparent through Discovery's windows. But it required Shriver and Bolden to expend half of their entire fuel supply in the first 40 minutes of the five-day mission, just to reach the desired altitude. And if anything went wrong with Hubble, they had to conserve whatever was left to rendezvous with it, fix it, deploy it again and still have enough to return safely home. In fact, the engine firing to bring Discovery back to Earth from Hubble's



Hubble, while still in the grasp of Discovery's robot arm, during the deployment of the solar arrays



The STS-31 crew monitors Hubble's deployment from Discovery's flight deck

➤ altitude lasted five minutes, 60 per cent longer than earlier flights.

STS-31 launched Hubble to space on 24 April 1990 and the next morning Hawley hoisted the telescope out of the payload bay with the 15m-long robot arm. Umbilical power was disconnected as planned, leaving Hubble with only two hours on internal batteries before its solar arrays needed to be unfolded and start generating their own electricity. One array opened perfectly; the other did not. In the

Shuttle's airlock, McCandless and Sullivan donned their spacesuits and were ready to go outside and fix it. Fortunately, a software error was at fault and the second array unfolded without needing astronaut intervention.

Historic moment

In this moment, euphoria and disappointment were peculiarly juxtaposed. The astronauts lost their chance to spacewalk, missing a golden opportunity to photograph

Hubble from the outside and win a *National Geographic* cover shot. Inside Discovery, however, Shriver, Bolden and Hawley could only gaze in dumbstruck astonishment as the glittering Hubble was released to begin its orbital career, high over the Andes mountains.

Momentarily distracted, the spell broke when all three men shouted in unison: "Camera! Somebody grab a camera!"

A remarkable voyage of discovery had got underway, but the harsh space environment would inevitably exact

The impact of the Challenger disaster

The tragic loss of Space Shuttle Challenger meant Hubble's launch plans were put on hold

When Shuttle Challenger exploded shortly after liftoff in January 1986, killing its seven-member crew – including teacher Christa McAuliffe – the heart and soul was torn from America's space community. But for Hubble, already months behind schedule and massively over budget, the unwelcome respite of the tragedy offered additional breathing room for it to evolve into a more capable instrument for astronomy.

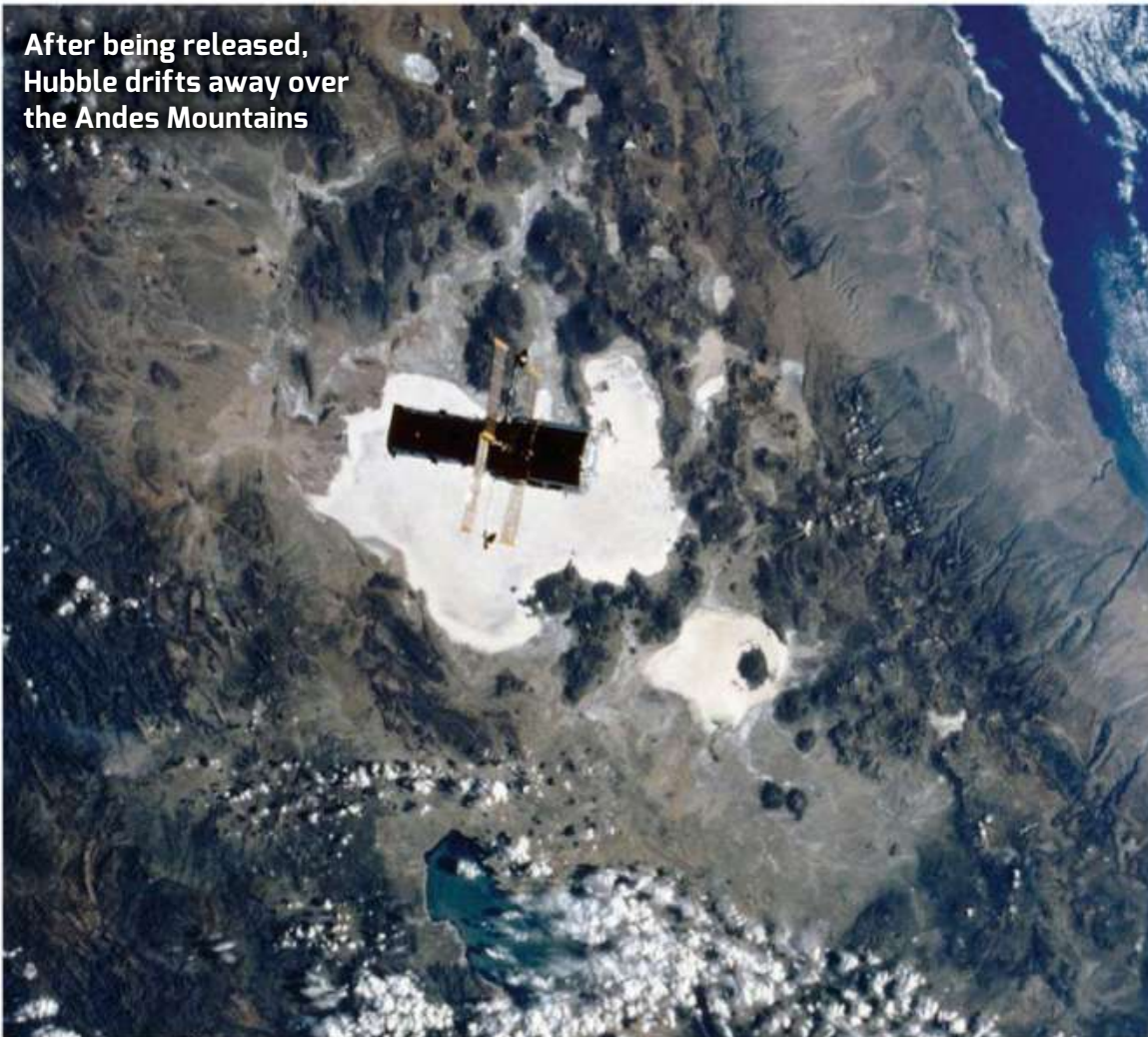
In June 1986, the telescope sailed through thermal vacuum chamber testing and the enforced post-Challenger downtime enabled engineers to build additional 'maintainability' into its systems. More powerful solar array cells were installed, the redundancy of critical systems was improved, flight software was upgraded and more reliable connectors were fitted. Even Hubble's nickel-cadmium batteries, which had a history of failure, were replaced with higher-performing nickel-hydrogen ones. And high-fidelity training mock-ups allowed the crew to prepare for one of the most difficult launches in Shuttle history.

But despite its promise to answer cosmological mysteries, Hubble was not at the head of the queue when the Shuttle returned to flight in September 1988. NASA needed to put two tracking and data-relay satellites into orbit to support future Shuttle crews and Hubble itself. Plus, the Department of Defense had a long line of classified military missions waiting for launch. Two planetary space probes, the Venus-bound Magellan and the Galileo voyage to Jupiter were tied to immovable launch windows in 1989. Only when they had flown was it Hubble's turn.

The Challenger disaster put Hubble launch plans on hold



After being released, Hubble drifts away over the Andes Mountains



its toll. Protected by Earth's magnetic field from the unbridled ferocity of the Sun, Hubble would still battle high radiation levels, micrometeoroid impacts, crumbling insulation and cracked thermal blankets. Sweeping temperatures as the telescope moved from direct sunlight to frigid darkness would cause its solar arrays to jitter, impairing some early observations. Yet it has survived and thrived for three decades.

With the Shuttle retired since 2011, Hubble is currently unreachable by astronauts. There has been talk of sending robotic vehicles to guide it to a controlled re-entry and Sierra Nevada Corporation proposed using its Dream Chaser spacecraft to service the telescope sometime in the 2020s. But for now, only one thing is certain. Time and fortune will be the final arbiters of how much longer this astronomical jewel can endure.

OXFORD SCIENCE ARCHIVE/PRINT COLLECTOR/GETTY IMAGES, NASA X 3,

Interview

Dr. Kathy Sullivan

A veteran of three Space Shuttle missions and the first American woman to walk in space, Kathryn D. Sullivan left NASA in 1993 and went on to become Administrator of the National Oceanic and Atmospheric Administration. Here she remembers her part in the 1990 mission that launched Hubble

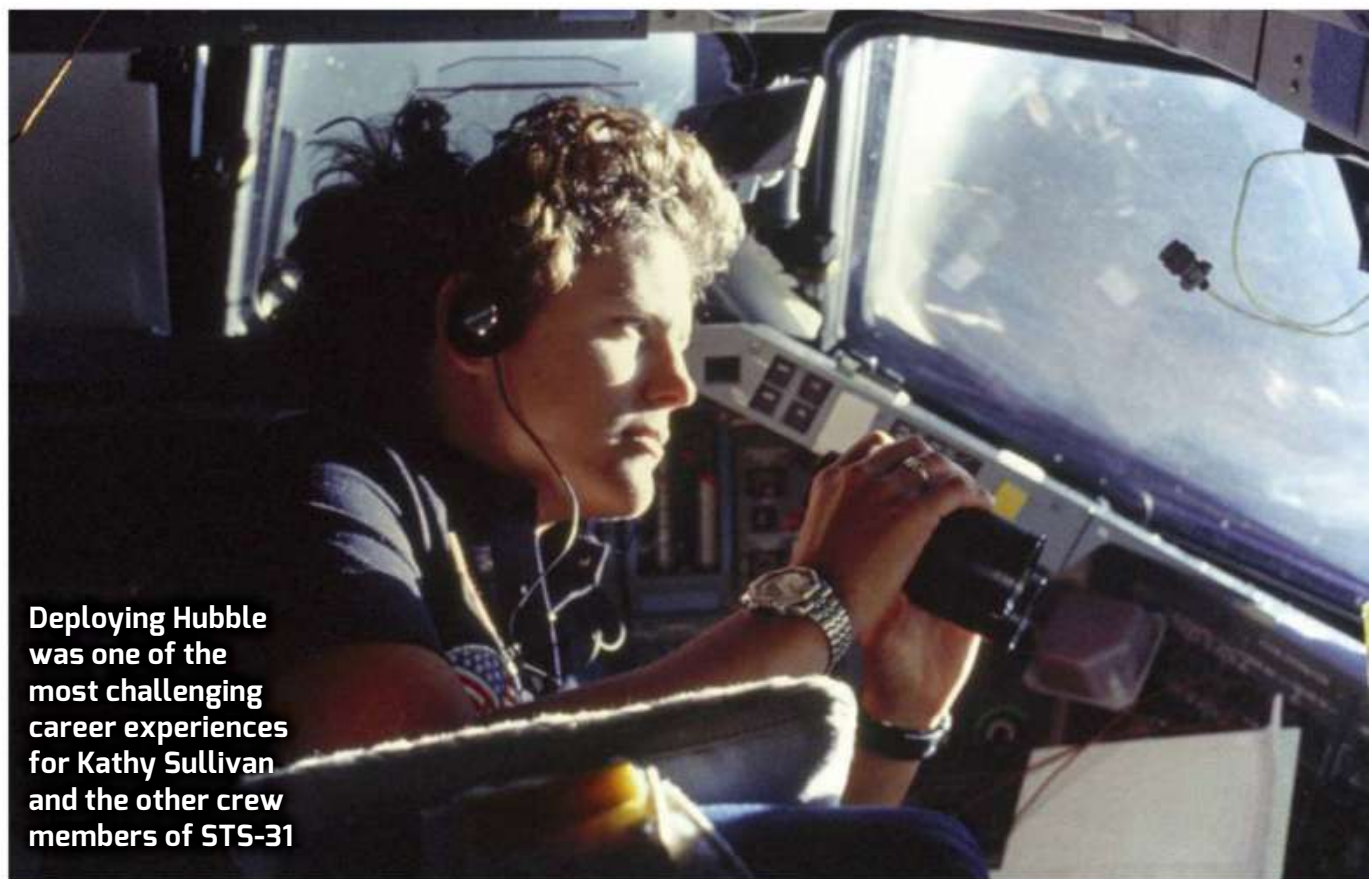
Working in England surprised Kathy Sullivan. Invited to see Hubble's solar arrays, she took an overnight flight from Washington, D.C. to Heathrow,

then drove to Bristol. She and Bruce McCandless donned lab suits and gloves, ready for work, but British Aerospace had other ideas: a formal lunch.

"We're crazy Americans; we don't break for lunch at times like this," she recalls. "Then we go to this lovely executive dining room, which we realised was to show off to the astronauts that the senior executive team of British Aerospace were there. Lovely lunch, thank you very much, but then they started offering us beer and wine. Bruce and I looked at each other. We don't have a drop of alcohol before working on flight hardware; not a chance. We were astonished!"

Of the mission to launch the historic telescope, she remembers that the spherical nature of Earth was clearly apparent from 612km. "The curvature was more pronounced than the distance that you could see," says Sullivan. "We were on one of those passes where from the geometry of the orbit you could see east to west along the Gulf Coast; a long period of time where you're looking due north into the interior of the United States." All at once, they spotted the lakes of Kansas, not clearly visible from the Shuttle's normal altitude. Steve Hawley, a native Kansan, excitedly pointed out his home state. "That became one of

"I was just so absorbed with where we were in the deployment and how difficult it had been to get to that point, I was really entirely about: this has got to work, let's just get this done."



Deploying Hubble was one of the most challenging career experiences for Kathy Sullivan and the other crew members of STS-31

our taglines," quips Sullivan. "Wait, that must be Kansas!"

Hubble's glistening insulation made it the brightest payload launched by the Shuttle. "It was a sparkly spacecraft," says Sullivan. She wanted to acquire "forensic engineering" photographs as it left Discovery. "I had all the cameras configured as soon as Steve began to move Hubble up out of the payload bay. Not for vacation pictures, but so the engineers on the ground would have very high-resolution detailed photos that confirm the physical

condition of the telescope as it was lifted out of the payload bay."

But she missed Hubble's actual release, for she and McCandless were in the airlock, ready for a spacewalk. Was she disappointed? "Honestly, at that moment, no. I was just so absorbed with where we were in the deployment and how difficult it had been to get to that point, how little time was really left and how little margin was left on the batteries. I was really entirely about: this has got to work, let's just get this done."





▲ Turning 25

RELEASED: 23 APRIL 2015

This image of a cluster of young stars, known as Westerlund 2, was released to celebrate Hubble's 25th anniversary. Located about 20,000 lightyears away, the thick green and blue clouds show where stars are forming – some will be only one to two million years old.



Cosmic horseshoe ➤

RELEASED: 19 DECEMBER 2011

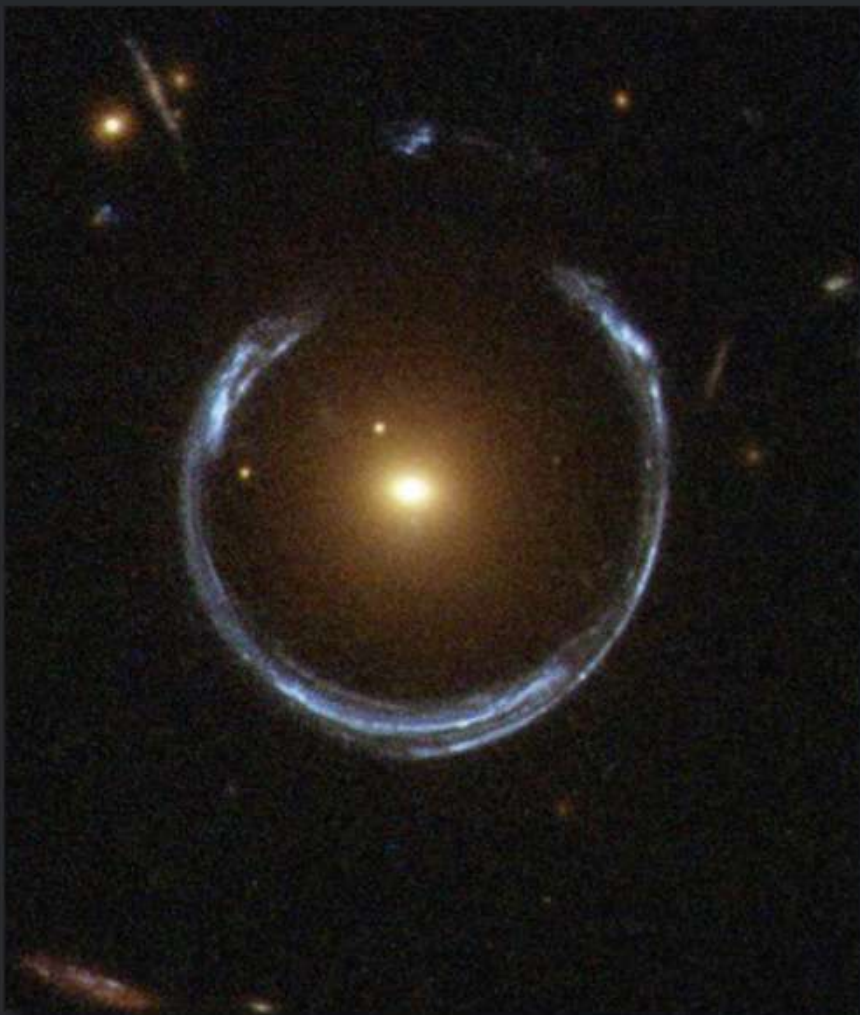
The blue horseshoe shape in this image is the result of ‘gravitational lensing’, where light from a distant galaxy has been magnified and warped by the strong gravitational pull of a massive galaxy in the foreground. If the source, lens and observer are all aligned (as is the case in this image), the light forms a circle – which is known as an ‘Einstein ring’.



▲ Martian storms

CAPTURED: 26 JUNE 2001

Orange dust storms swirl across the surface of the Red Planet. One large storm system whirls high above the northern polar cap, while another spills out of the giant impact basin of Hellas Planitia in the southern hemisphere.



NASA/ESA/THE HUBBLE HERITAGE TEAM (STSCI/AURA) A. NOTA (ESA/STSCI), AND THE WESTERLUND 2 SCIENCE TEAM, NASA/ESA AND THE HUBBLE HERITAGE TEAM STSCI/AURA, ESA/HUBBLE & NASA

From white knight to white elephant

Almost straight after deployment, Hubble's optics were found to be flawed. But the telescope eventually recovered its reputation

By Ben Evans

Barbara Mikulski, the Democratic senator for Hubble's home state of Maryland, was livid. In time, she would become one of the space telescope's staunchest proponents, but in July 1990 her stinging words spoke instead of a "techno-turkey" and a waste of taxpayers' money. Future US vice president Al Gore agreed that Hubble had turned from a scientific marvel into tangible proof of NASA's quality-control failings. Late-night television talk-show hosts were even more scathing; David Letterman compiled a list of top 10 Hubble excuses. But what happened to twist this white knight of astronomy into a white elephant of ridicule?

All new spacecraft suffer teething troubles and Hubble was no exception, with sporadic communication dropouts, drifting star trackers and snagged coaxial cables. More serious were

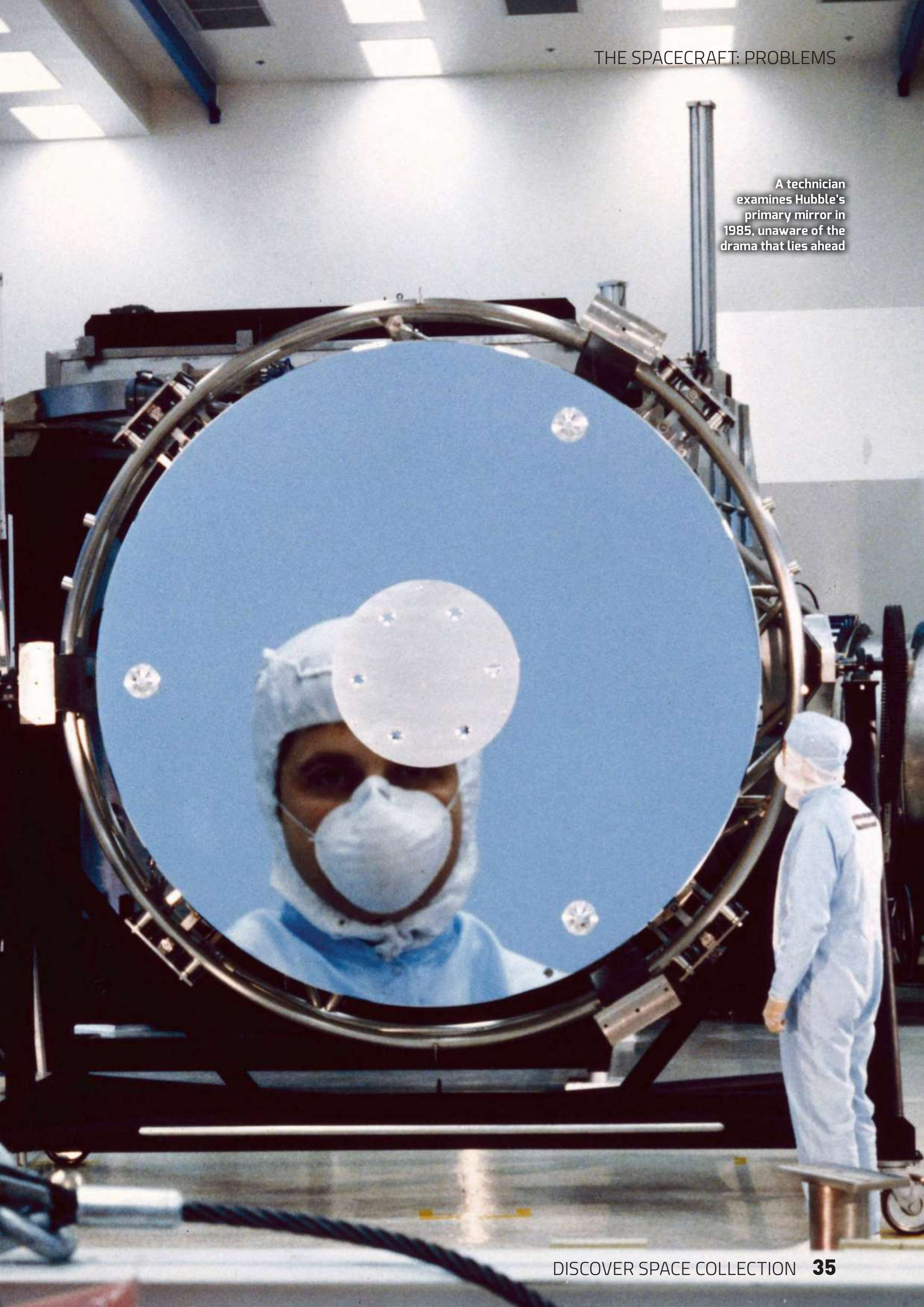
extreme temperature variations as the telescope moved from direct sunlight into orbital darkness and materials in its solar array booms began to warp. Its orientation system worsened the problem, causing the arrays to wobble. And since the booms only stabilised just prior to sunset, Hubble could point itself accurately for barely a fraction of each orbit. Computer workarounds were devised and in May 1990 it photographed a double star in the Carina constellation. The pictures were praised for their crystalline clarity.

A tiny flaw

But it proved a false dawn. In late June, Hubble failed a focusing test. Its mirrors had been carefully ground to focus incoming light from celestial objects, but the images were smeared by a halo-like fog. The cause was spherical aberration in its primary mirror. Perkin-Elmer – the optics contractor about whom NASA harboured such



A technician
examines Hubble's
primary mirror in
1985, unaware of the
drama that lies ahead





▲ The spiral galaxy M100. Top: image taken in 1993 with the flawed primary mirror. Bottom: image taken by the Wide Field Camera 3 after it was installed in 2009

✎ misgivings a decade earlier – had removed too much glass and polished it too flat. The flaw was tiny, two-fiftieths as broad as a human hair, but that was more than enough to keep Hubble from delivering the razor-sharp imagery that NASA had promised the public and its political masters.

The mood, remembered program scientist Ed Weiler, was like falling from the summit of Mount Everest to the floor of Death Valley. Even NASA's newest class of astronauts were not immune to the frenzy of media questions. The agency launched an investigation, headed by Jet Propulsion

Laboratory director Lew Allen. His report, published in November, blamed an optical device called a reflective null corrector, which was supposed to determine the figure of Hubble's mirror. But the location of the null corrector's lens had been incorrectly measured and it guided the polishing machine to shape a perfectly smooth mirror with the wrong curvature.

If further proof was needed, the curvature flaw in the mirror exactly matched the flaw in the null corrector. A second null corrector had identified the mistake but was overruled.

Technicians had simply assumed that

both mirror and null corrector were perfect and rejected data from other independent tests which indicated otherwise. Allen harshly criticised Perkin-Elmer's quality-control practices and NASA for failing to address them.

Spherical aberration proved very bad news for the WFPC and FOC instruments, which suffered poor spatial resolution and an impaired ability to see distant objects. Hubble's spectrographs were less severely affected because they needed less focused light, but the wobbling solar arrays virtually crippled the HSP. However, there was a silver lining. While the incontrovertible fact remained that the mirror was flawed, it was in fact flawed very precisely. By knowing its exact shape, appropriate steps could be taken to fix it and, in 1991, Ball Aerospace began building a set of corrective optics.

Turning the tables

Still, even this compromised Hubble was far more capable than any ground-based observatory. Pictures of the Orion Nebula resolved small-scale structures to an unprecedented standard, although the fuzziness of spherical aberration meant that surface features on the dwarf planet Pluto were blurred and the energetic core of the symbiotic star R Aquarii was indistinct. Computer algorithms and microwave image-processing techniques were put to work to deduct the halo effect and restore the pictures. By early 1992, thousands of observations of hundreds of celestial objects had been made and a quarter of all papers presented to the American Astronomical Society used Hubble results.

The telescope revealed that the Large Magellanic Cloud – one of our nearest galactic neighbours – resides 169,000 lightyears away. Data from 27 Cepheid variable stars allowed astronomers to tentatively peg the age of the Universe close to 15 billion years. Hubble recorded the most distant galaxy ever seen (10 billion lightyears away) and, though hamstrung by spherical aberration, it could still see luminous 'knots' of gas and dust at its primordial core with a resolution

The fallout from Hubble

For NASA, the discovery of Hubble's flawed optics was a bitter blow after the Challenger disaster and another knock to its operational reputation

NASA's Marshall Space Flight Center had a bad press in 1990. Just four years after Challenger – the failure of whose solid rocket boosters also came under Marshall's remit – it now endured the wrath of the public and politicians alike over Hubble. In July, *The New York Times* wrote that if Kodak-Itek's pricier bid for the mirror had been picked, its two independent checks of polishing quality would have caught the spherical aberration. It was another unwanted problem facing a beleaguered NASA.

For much of 1990, the Shuttle fleet was grounded by fuel leaks. Plans to build Space Station Freedom were over budget, behind schedule and forever sitting on a knife-edge of cancellation. And the Space Exploration Initiative to return humans to the Moon and onward to Mars looked set to die with a whimper.

By 1991, Freedom came within one congressional vote of cancellation. A year later, the Moon-Mars plan breathed its last. And the astronauts charged with fixing Hubble were told by NASA Administrator Dan Goldin that their flight was critical; if they failed, so too would the political will for the station. In 1993, NASA's Mars Observer failed as it

neared the Red Planet and rumour abounded that Hubble's new WFPC 2 instrument might be faulty.

President Bill Clinton informed Goldin that if the repair failed, NASA would be restructured. Some engineers hoped to celebrate New Year 1994 in Acapulco, but if things went badly with Hubble they joked darkly that it might turn out to be their place of permanent exile.

Space Station Freedom (which later evolved into the ISS) was almost cancelled after the problems with Hubble were discovered



Even with defective optics, Hubble proved its enormous potential with shots like this one of Mars taken in December 1990



10 times finer than ground-based instruments on Earth.

Tightly concentrated stars in active galactic nuclei and enormous plasma 'jets' yielded tantalising evidence for black holes, which were suspected but still hypothetical at the time. Data from 1992 hinted that a black hole 2.6 billion times more massive than the Sun sat

at the heart of the elliptical galaxy M87. And close observations of X-shaped 'lanes' of gas and dust in the Whirlpool Galaxy afforded a glimpse around one of these mysterious monsters.

Closer to home, Hubble verified the presence of ozone in Mars's atmosphere and photographed a hood-like cloud over its north pole. Observations of

Jupiter revealed powerful aurorae in ultraviolet light for the first time and directly measured the atmosphere of its volcanic moon Io, revealing sulphur dioxide 'frost' on its surface. The telescope tracked an equatorial white spot on Saturn and analysed albedo variations on the surfaces of Pluto and its large companion, Charon.

Hubble studied star-forming regions in the Tarantula Nebula and found one of the central stars in the galaxy NGC 2440 was the hottest ever recorded – over 200,000°C. Shell-like rings of gas encircled the famous Supernova 1987A and the telescope watched the process of 'starbirth' in numerous globular clusters. It acquired spectroscopic data for the young supergiant star Melnick 42 and observed the rare element boron in HD 140283 – the aptly-named 'Methuselah Star' – which is thought to have formed not long after the Big Bang, right at the dawn of time.

So, after a rocky start, Hubble came out victorious in the end.



Galactic enigma

RELEASED: 17 FEBRUARY 2011

Star formation plays a key role in the development of planetary systems and the evolution of galaxies, yet still so little is known about what kick-starts the process in the first place. This is particularly the case for a type of galaxy called a 'flocculent spiral', such as NGC 2841 shown here. These galaxies feature short spiral arms, as opposed to prominent and well-defined galactic limbs.



Supernova blast

RELEASED: 10 OCTOBER 2000

This blue streak is part of the expanding blast wave from a colossal stellar explosion in the Cygnus Loop nebula, which occurred about 15,000 years ago. Gas and dust in the blast wave is travelling at over five million km per hour. The remnants of supernovae play an important role in star formation, feeding stellar nurseries with vital heavy elements and compressing interstellar gas.



Lunar parade ►

RELEASED: 5 FEBRUARY 2015

Three of Jupiter's largest moons parade across the gas giant. The top image was taken by Hubble at the start of this rare event. The yellow dot just off centre is Io, the orange dot on the left is Callisto and the black dots are the shadows of both moons plus that of Europa (which isn't in view). The bottom image shows the end of the event – 42 minutes later – with the white dot of Europa now visible.



NASA, ESA AND THE HUBBLE HERITAGE (STSCI/AURA) ESA/HUBBLE COLLABORATION,
ESA & DIGITIZED SKY SURVEY (CALTECH), NASA/ESA/HUBBLE HERITAGE TEAM

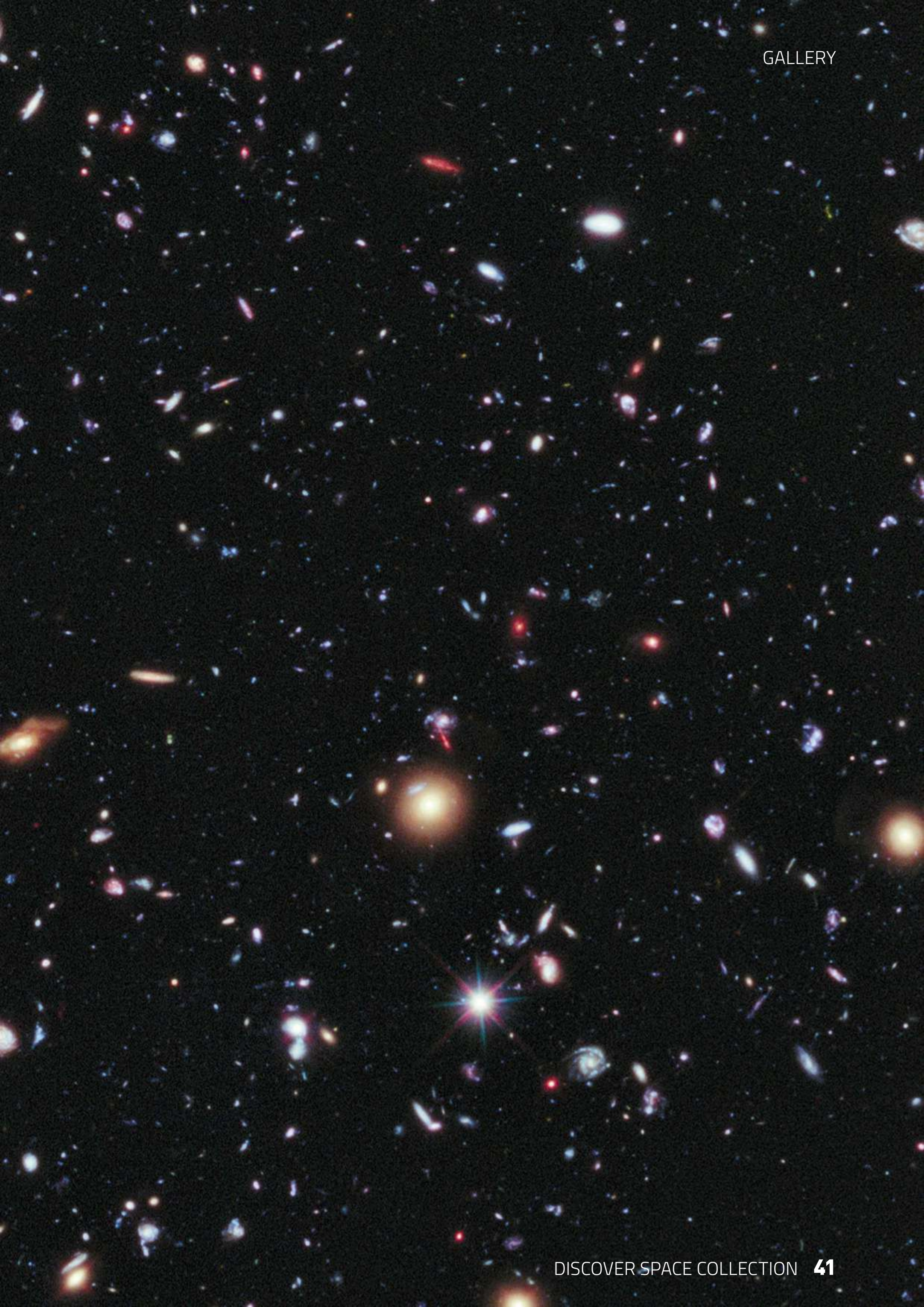


NASA/ESA/G. ILINGWORTH/D. MAGEE AND P. OESCH (UNIVERSITY OF CALIFORNIA/
SANTA CRUZ) R. BOUWENS (LEIDEN UNIVERSITY) AND THE HUDF09 TEAM

The dawn of time

RELEASED: 25 SEPTEMBER 2012

This iconic Hubble eXtreme Deep Field (XDF) image is of a small patch of sky in the constellation of Fornax. It's the deepest image ever made of the Universe, and combines over two million seconds of exposure time with data from previous images captured in 2002, 2003 and 2009. The Universe is 13.7 billion years old, and this image reveals galaxies that span back 13.2 billion years in time.



Astronaut Story Musgrave prepares to be elevated to the top of Hubble to install protective covers on its pointing control system



Bringing Hubble back to life

The repair mission to fix Hubble's optics was hugely challenging, but its success restored NASA's reputation

By Ben Evans

Hubble was always intended to be maintained – keeping it functional and up to date with technological change enabled NASA to sell it to Congress. Servicing it required the Shuttle's flexibility, its robot arm, its astronauts and ingenious teams on Earth to work with the synergy of a ballet and fix anything that needed fixing. The Shuttle had proved its mettle as a highly capable spacecraft, but correcting the space telescope's flawed optics would stretch that capability to its limits.

Kathy Sullivan and Bruce McCandless knew the telescope was a priceless national asset and helped to build the tools to service it. Even the tiniest potential problem had to be addressed: from the correct size of wrenches, bolts and fasteners to knowing exactly how a space-suited astronaut wearing gloves with the dexterity of a welder's mittens could reach an intricate electrical system or hard-to-access equipment bay. McCandless, Sullivan and the engineers who they worked with were determined that the words "Hey, guys, this tool doesn't fit" would never be spoken on a Hubble servicing mission.

Since the flaw in the telescope's primary mirror was well understood, it was recognised that a set of carefully designed corrective optics – Hubble's \$50 million 'spectacles', the media jokingly named them – should be enough to rejuvenate its vision. Ball



▲ A ratchet tool used to repair Hubble. Many of the tools were specifically developed for the STS-61 mission

Aerospace built the Corrective Optics Space Telescope Axial Replacement (COSTAR), whose mechanical arms would deploy 10 coin-sized mirrors into Hubble's focal plane to refocus light from the primary mirror before it reached the instruments.

Testing training

Hubble servicing flights would demand at least four spacewalks, twice as many as had ever been done by the Shuttle. At six hours apiece, each spacewalk would put astronauts in a hostile environment of near-total vacuum, huge temperature extremes and lethal radiation. And astronauts inside the Shuttle would face long hours of intense concentration to orchestrate the repairs, prepare spacesuits and control the robot arm. In 1991, NASA decided to forgo an early servicing flight and stick with original plans for an



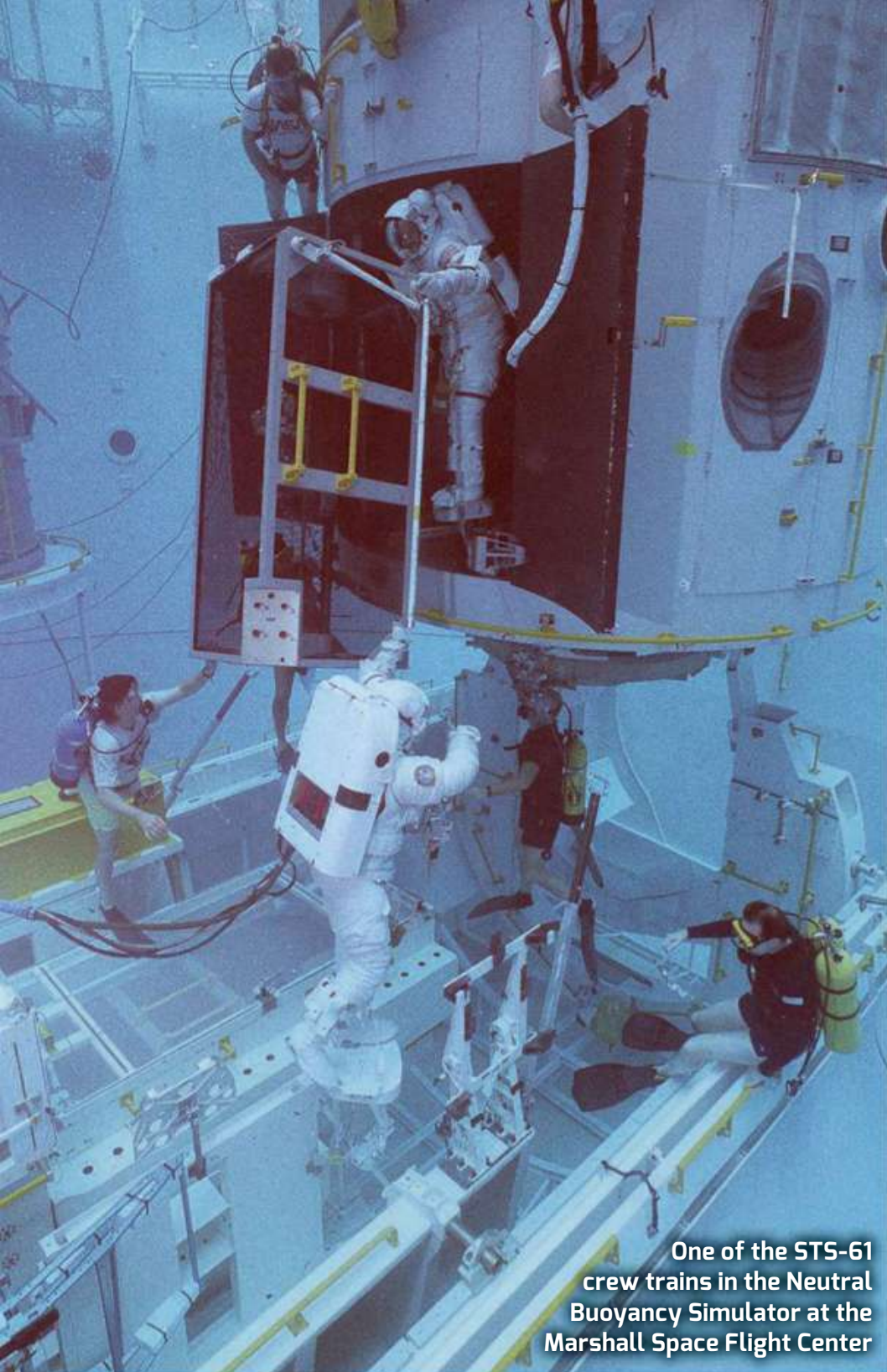
▲ Astronaut Jeffrey A. Hoffman trains for the mission using virtual reality – an emerging technology at the time

all-out repair to fix the optics on Shuttle mission STS-61 in 1993.

Former chief astronaut John Young recommended 'end-to-end' training for the crew at various NASA establishments, including the Shuttle simulator at the Johnson Space Center in Texas and integrated spacewalking/robotics practice in the neutral buoyancy simulator at the Marshall Space Flight Center in Alabama. This training would be far-reaching in scope, laying the groundwork not just to fix Hubble but also prepare astronauts to build a space station. The crew would use replica robot arms, clamber over a full-sized, high-fidelity mockup of the telescope, submerge themselves underwater in spacesuits and test-drive the evolving technology of virtual reality.

In 1992, astronaut Story Musgrave was assigned to STS-61. With four

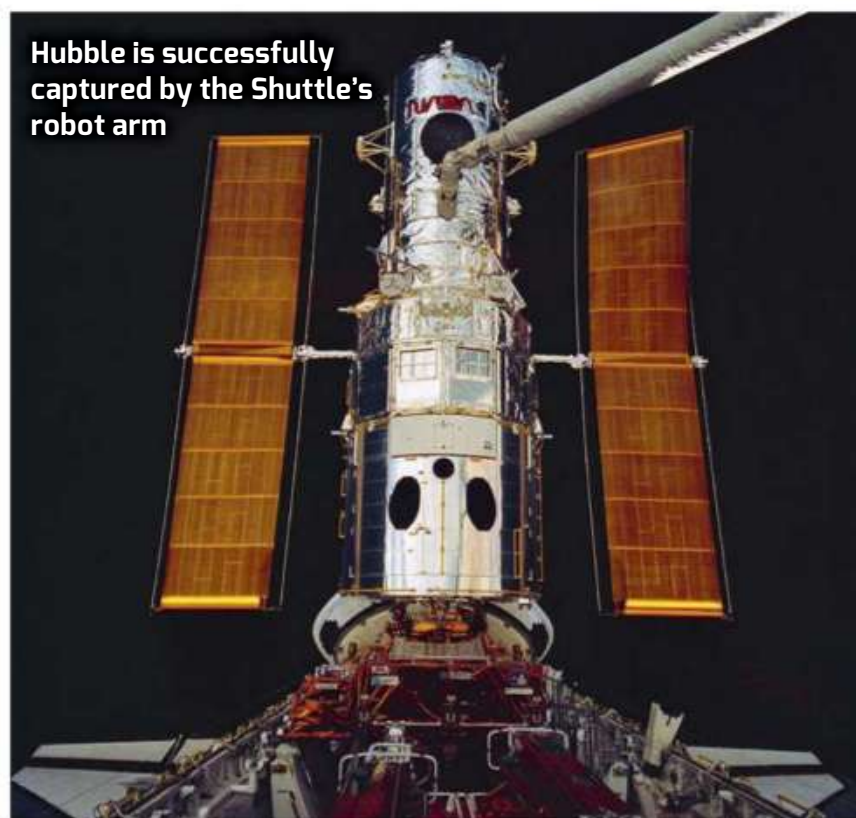
NASA X3



One of the STS-61 crew trains in the Neutral Buoyancy Simulator at the Marshall Space Flight Center



▲ The crew of STS-61. Left to right: F. Story Musgrave, Richard O. Covey, Claude Nicollier, Jeffrey A. Hoffman, Kenneth D. Bowersox, Kathryn C. Thornton, and Thomas D. Akers



Hubble is successfully captured by the Shuttle's robot arm

➤ spaceflights under his belt, a long-time association with Hubble and a veteran of the first Shuttle spacewalk, he was an obvious pick. Years later, he quipped that training for this mission was so intense that his only moments of peace came while sitting in the dentist's chair.

For the highly competitive astronaut corps, a seat on STS-61 was a plum assignment, coveted by all. One day in mid-1992, NASA's director of flight crew operations Don Puddy was chatting to astronaut Jeff Hoffman.

"Well," said Hoffman, "I'd sure like to fly this Hubble mission."

Puddy smiled. "Yeah, you and the rest of the office!"

But Hoffman had a trump card up his sleeve. NASA wanted the crew – four spacewalkers, robot arm operator, commander and pilot – to be experienced astronauts. At the time, there were very few seasoned spacewalkers in the office. Hoffman was one of them – and an astronomer to boot. That summer, he and spacewalk veterans Kathy Thornton

and Tom Akers got the nod. By December, commander Dick Covey, pilot Ken Bowersox and European Space Agency robot arm expert Claude Nicollier joined them. With 16 previous Shuttle flights between them, they were the most experienced crew yet assembled.

Back from the brink

STS-61 would last 11 days with a record-setting five spacewalks. Backup spacewalker Greg Harbaugh trained with them, in case one of the crew became incapacitated, as almost happened when Musgrave suffered frostbitten fingers during an altitude chamber test. And although NASA concluded the mission was achievable, all fingers remained crossed on 2 December 1993 when Shuttle Endeavour roared into the night in hot pursuit of Hubble. Two days later, they reached the telescope and Nicollier grabbed it with the robot arm and anchored it in the payload bay.

Working in two alternating teams,

Hoffman and Musgrave, and Thornton and Akers spacewalked for five consecutive days, spending 35 hours outside the Shuttle and using 200 tools, from ratchets and sockets to portable work-lamps and articulating foot restraints. Fixing Hubble did not demand immense physical strength, but did need finesse and technical coordination. Years later, Covey recalled those adrenaline-charged days with justifiable pride. "There wasn't anybody that was chilling down on the middeck," he told an interviewer. "Everybody was up top, working."

On the first spacewalk, Hoffman and Musgrave replaced two rate sensing units, whose gyroscopes – half of which had failed – helped Hubble track astronomical targets. Next day, Thornton and Akers replaced the twin solar arrays. The first rolled smoothly into its storage canister, but a bent strut on the other prevented it from doing likewise and the spacewalkers had little option but to cast it overboard.

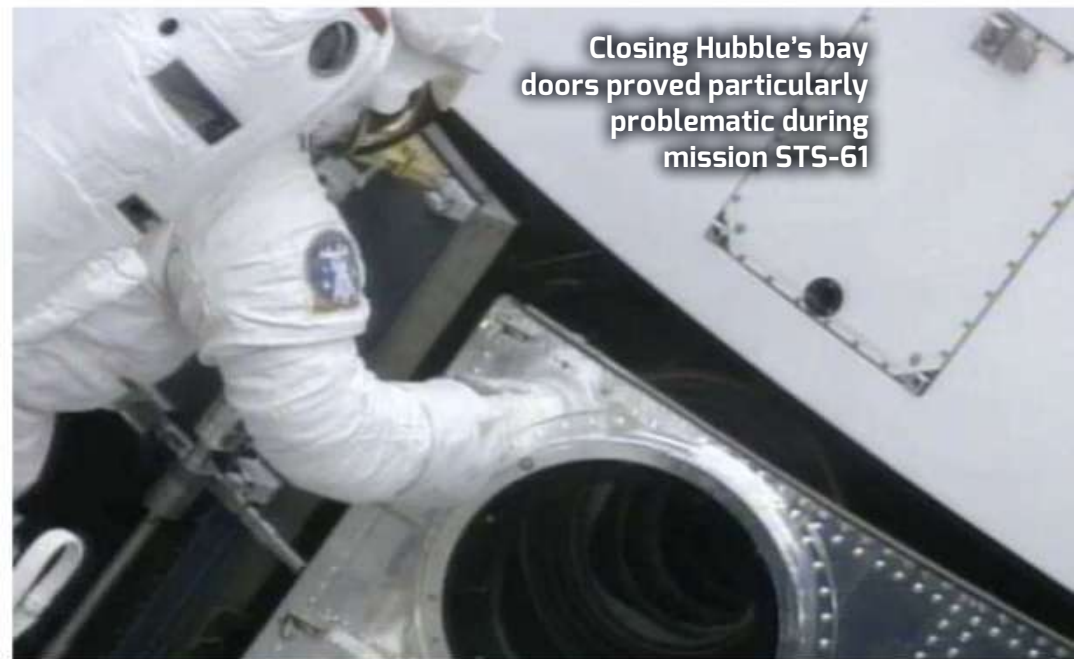
Never a straightforward mission

Upgrading Hubble called for some of the most complex spacewalks ever planned. Inevitably, these missions rarely went according to schedule

All five servicing missions between 1993 and 2009 endured their fair share of difficulty. On STS-61, astronauts struggled to close Hubble's equipment bay doors, their latches having become warped by uneven solar heating. And on the second servicing flight, STS-82 in February 1997, the telescope's solar arrays unexpectedly 'windmilled' a quarter turn. Although this carried safety implications for the crew, it was triggered by air venting from the Shuttle's airlock and the spacewalks proceeded without incident.

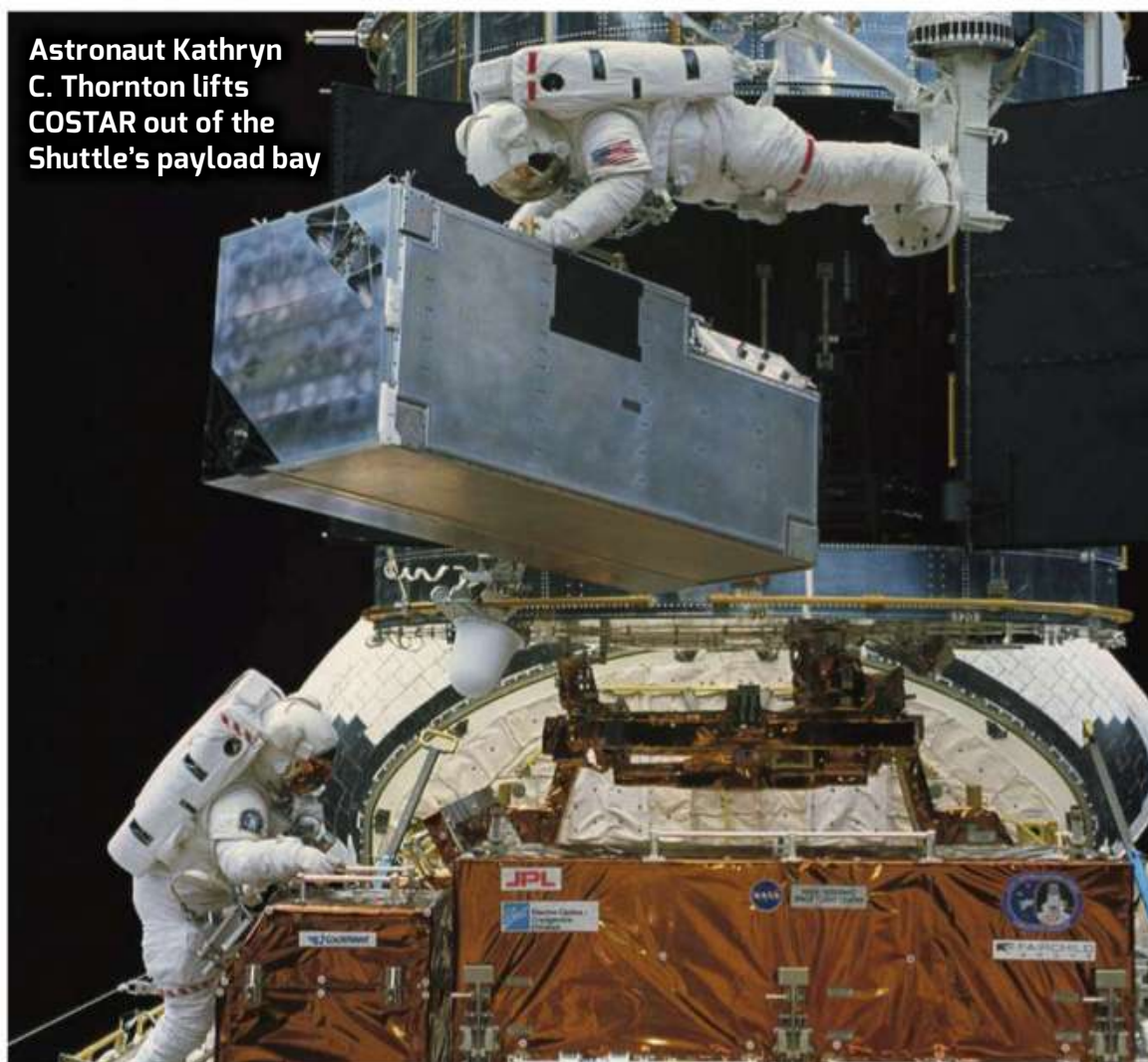
A third servicing mission was brought forward to December 1999, following a spate of hardware failures, which crippled two-thirds of Hubble's gyroscopes. Flight controllers shut the telescope down for its own protection and NASA launched a 'call-up' Shuttle, STS-103, which replaced the gyroscopes but encountered its own problems, from stubborn valve covers to visibility issues while fitting Hubble's new computer.

The fourth mission, STS-109 in March 2002, was delayed when further Hubble failures added more work to an overflowing jobs list. Tasked with replacing the telescope's electronic heart, the crew battled stiff connectors and bolts, as well as spacesuit troubles in the form of water leaks and a failed telemetry sensor. It was not the first time the suits



Closing Hubble's bay doors proved particularly problematic during mission STS-61

had caused trouble. On STS-61, the communications link from Thornton's suit briefly hiccuped and Akers had to serve as her relay. And on the final Hubble visit, STS-125 in May 2009, a stubborn-to-remove handrail, stripped screws and troublesome power tools provided a stark reminder – if one was ever needed – that spaceflight is never routine.



Astronaut Kathryn C. Thornton lifts COSTAR out of the Shuttle's payload bay

Hoffman and Musgrave, on the third spacewalk, exchanged the WFPC instrument for the new WFPC 2, originally a ground-based spare but later upgraded with an optical corrector. They also installed two magnetometers. Thornton and Akers plucked out the HSP instrument and slotted COSTAR into its place. And on the fifth day, Hoffman and Musgrave replaced overheating solar array drive electronics.

It took several more weeks before WFPC 2 was optically aligned, COSTAR fully deployed and the first images beamed back to Earth. On New Year's Day 1994, Hoffman was at home when the telephone rang.

"Jeff, hi," came the greeting. "Do you have any champagne left?"

"Yeah, I have a half-bottle in the refrigerator."

"Well, crack it open. We've just had the first pictures back from Hubble. It works!"

Interview

Dr. Story Musgrave

A veteran of the US Marine Corps with academic degrees in six subjects, from maths to medicine, F. Story Musgrave became NASA's preeminent authority on spacewalks. One of only a handful of astronauts to complete six space missions, he was payload commander on mission STS-61

“The most important deployment in history; a huge mission. The whole world was waiting for the results,” says Story Musgrave of the STS-61

mission. Musgrave, selected to lead the repairs on the mission, had previously communicated with the STS-31 crew from Mission Control and had worked on the space telescope since 1975. “You never can tell if it was a natural selection,” he says, but having done the first-ever Shuttle spacewalk, he seemed a logical choice. “You’ve got to reward the people that do all the work.”

The repair mission had a record-breaking five spacewalks. “There were 13 systems broken, so that dictates the mission and what we could’ve done,” Musgrave explains. “I could’ve done back-to-back spacewalks every day for five or six days.”

Musgrave was also the oldest spacewalker, aged 58. “It’s no more than a day’s work,” he says. “If it’s a demanding day’s work, you haven’t designed it right. You design it not to be special and not to be hard work, then you choreograph it.” Musgrave choreographed every detail down to the last screw or bolt. “You design for not having physical strength. You reserve the physical strength for performance margin, but I’m a total wimp. I design them to be done by anybody without physical force, so you have margin if you run into a surprise.”

With his expertise, Musgrave should have been ‘EV1’, the chief spacewalker, but he rejected it. “I tried to disempower



“There were 13 systems broken. I could’ve done back-to-back spacewalks every day for five or six days.”

◀ **Story Musgrave during the first of five spacewalks to repair Hubble in 1993**

myself, because if you’re too powerful the right answers don’t come,” he says. “People assume you’ve got the right answers and they don’t dare challenge the answers, so that’s why I refused the title of EV1. The best solution comes democratically. How Mission Control works is the whole team plays with the data, you challenge each other and finally converge on the right solution.” Musgrave wanted to be one of the gang.

Spacewalking was “...outrageous for sure”, especially working on the

Shuttle’s robot arm. “I was looking at the whole continent of Australia. The only sense of fear of heights that I have ever had in spaceflight was looking from the arm down into the payload bay and thinking I could fall.”

His four previous space missions as a flight engineer were totally different, carrying primary responsibility for Shuttle systems. “They didn’t want any spacewalker on STS-61 to be the flight engineer. They wanted us to concentrate on fixing Hubble – to concentrate on the back of the bus.”

THE SPACECRAFT: THE REPAIR MISSION





▲ Light echo

RELEASED: 17 DECEMBER 2013

This image shows the star RS Puppis, which is a Cepheid variable – a type of star that pulsates to a regular rhythm, varying in diameter and temperature, which causes changes in its brightness. RS Puppis varies in brightness by almost a factor of five roughly every 40 days. With rapidly brightening stars such as this, the light travelling directly from it arrives first, illuminating the dust clouds in a phenomenon known as a 'light echo'.



▲ **Sombrero Galaxy**

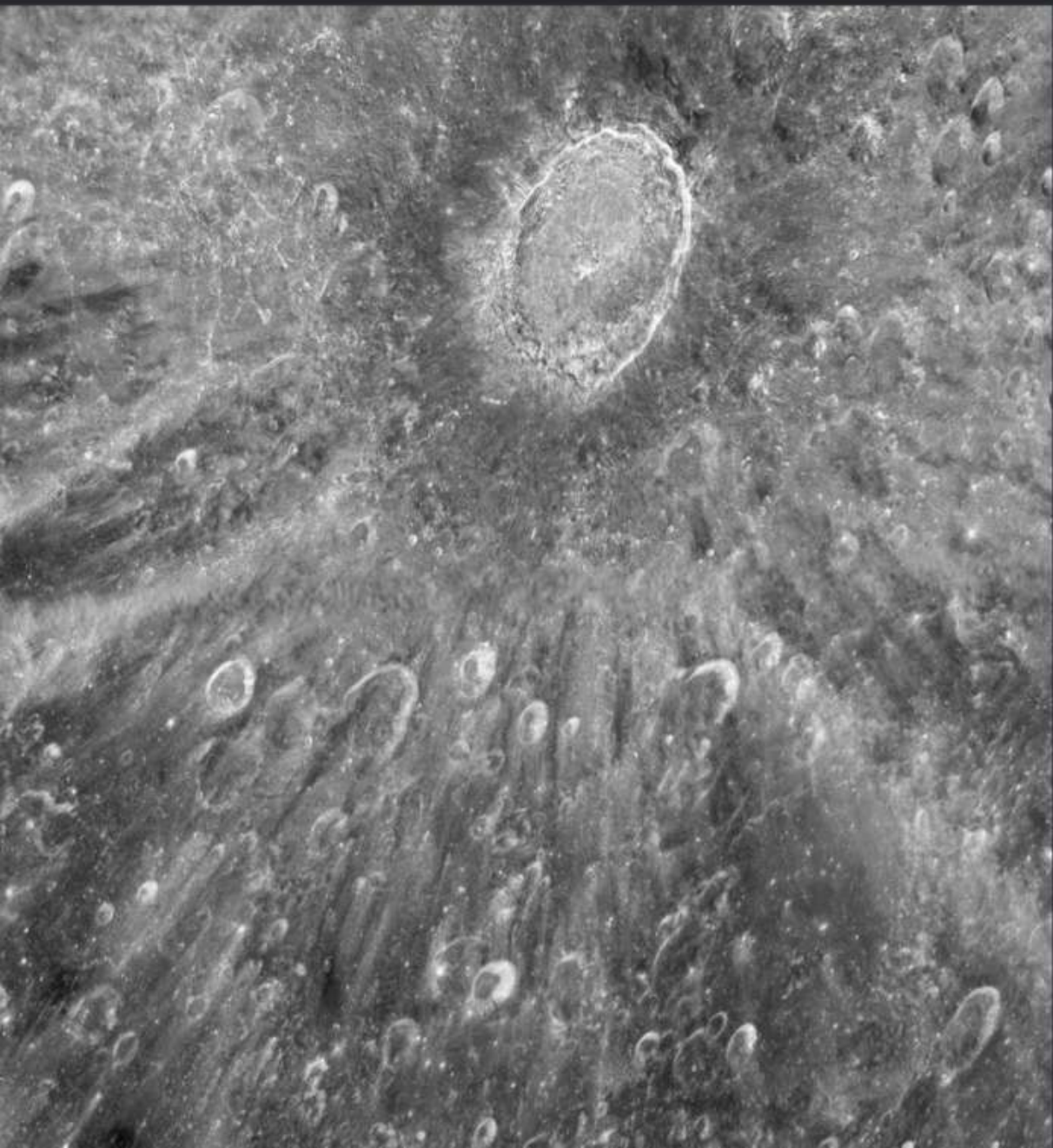
RELEASED: 2 OCTOBER 2004

The galaxy M104 is viewed edge-on from Earth, which makes it resemble the broad rim of a Mexican hat – hence the nickname Sombrero Galaxy. It is one of the most massive objects in the Virgo cluster of galaxies – equivalent to 800 billion suns – and can easily be seen through small telescopes on Earth.

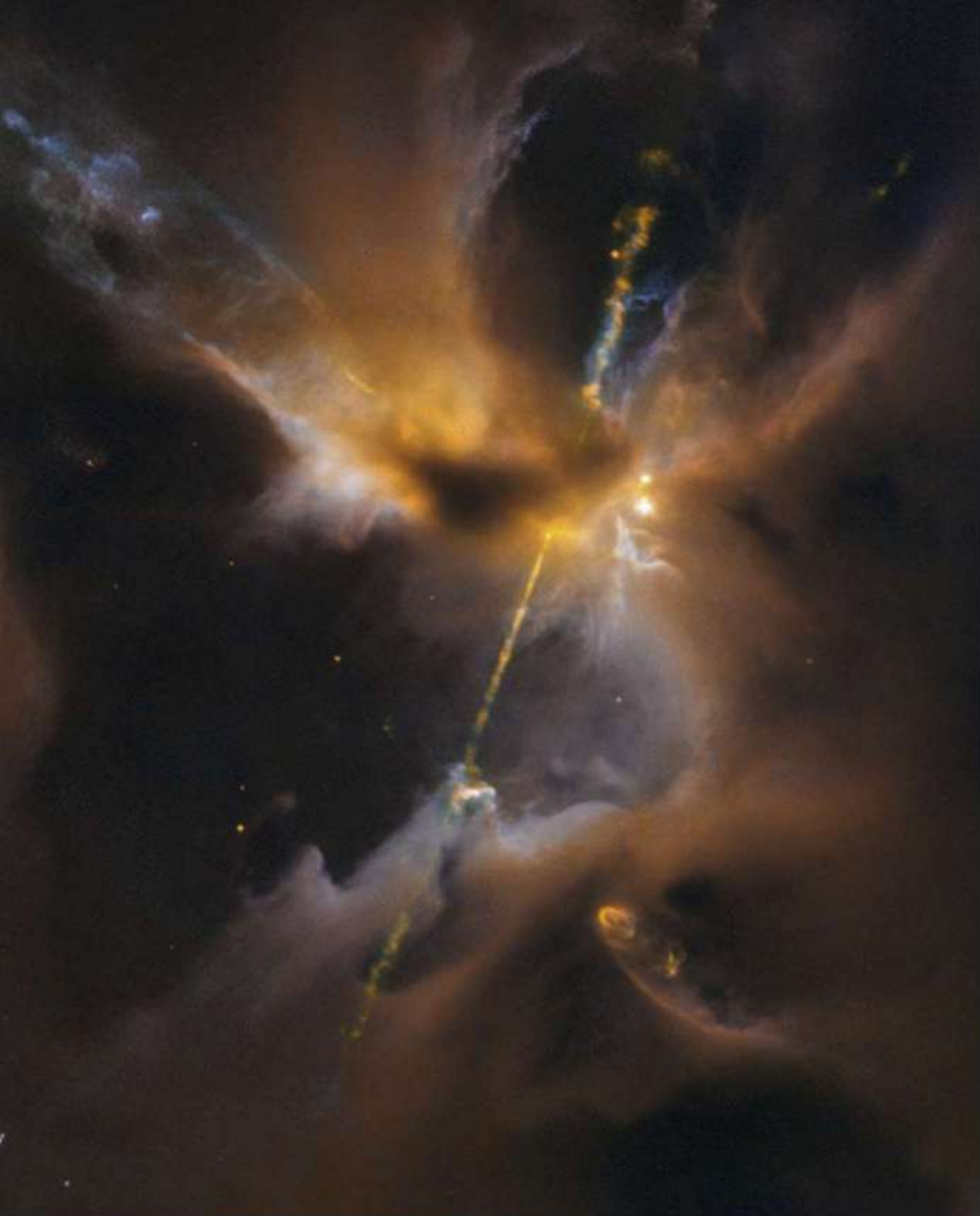
◀ **Moon mirror**

CAPTURED: 11 JANUARY 2012

This image shows the lunar impact crater Tycho. However, the aim wasn't to photograph the Moon, but practice for a future solar transit by Venus. As Hubble can't look directly at the Sun, astronomers planned to use our lunar neighbour as a mirror to capture reflected sunlight. This image was a practice run for the real event on 5-6 June 2012.



NASA/ESA AND THE HUBBLE HERITAGE TEAM (STSCI/AURA) HUBBLE/EUROPE COLLABORATION,
NASA/ESA AND THE HUBBLE HERITAGE TEAM (STSCI/AURA) NASA/ESA/D. EHRENREICH (INSTITUT DE
PLANÉTOLOGIE ET D'ASTROPHYSIQUE DE GRENOBLE (IPAG)/CNRS/UNIVERSITÉ JOSEPH FOURIER)



◀ Slicing through space

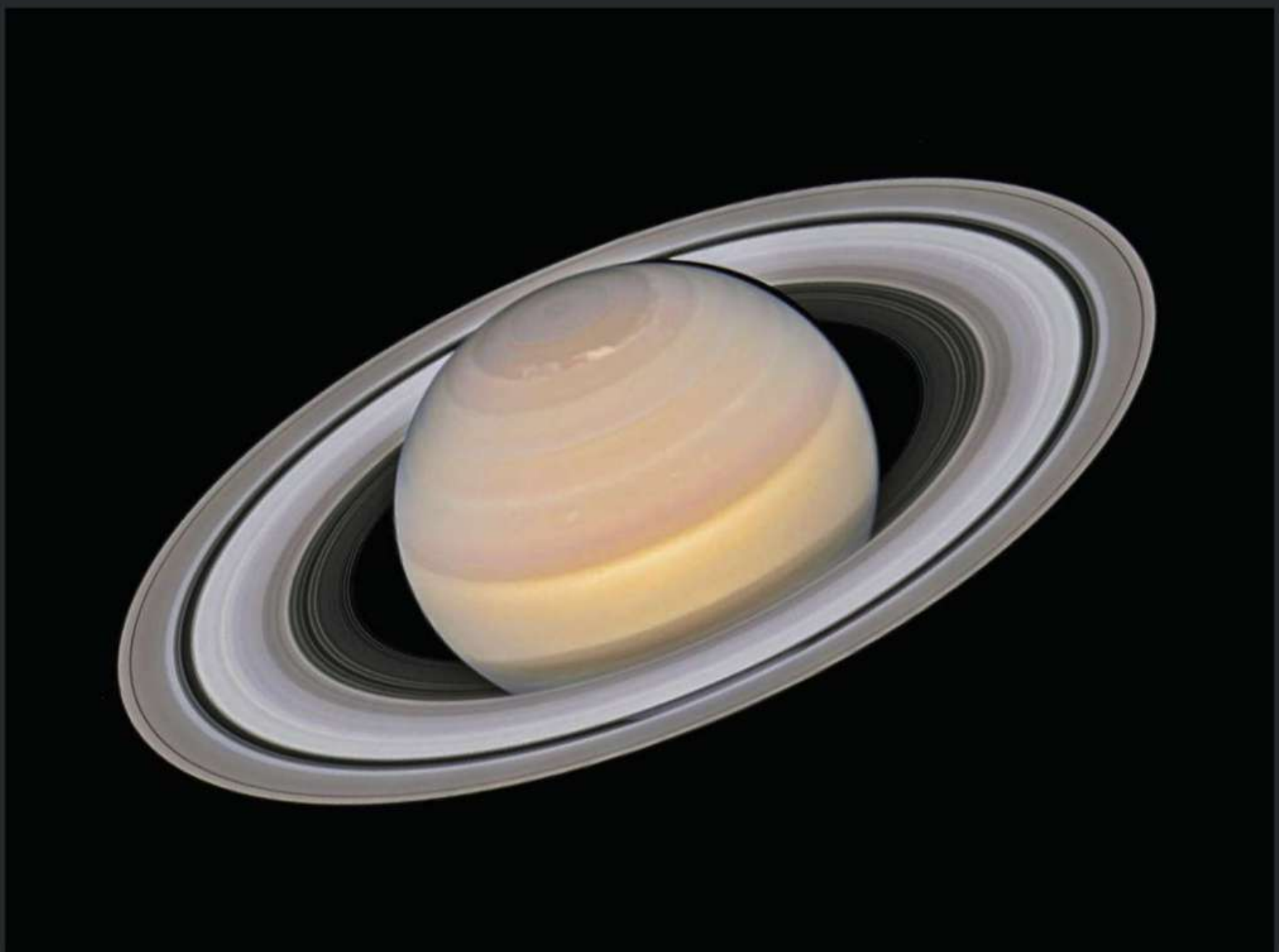
RELEASED: 17 DECEMBER 2015

Jets of energised gas, ejected from the poles of a young star, slice through the surrounding gas and dust, sweeping away the debris to create huge spaces and curved shock waves, known as Herbig-Haro objects.

▼ The ringed planet

CAPTURED: 6 JUNE 2018

Saturn has the most complex ring system in the Solar System. Mostly made of water ice, the rings are thought to have formed 200 million years ago – at the time of the dinosaurs during the Jurassic period. The banded structure of the planet itself is caused by wind and clouds at different altitudes.



ESA/HUBBLE & NASA/D. PADGETT (GSFC), T. MEGEATH (UNIVERSITY OF TOLEDO) AND B. REPURTH (UNIVERSITY OF HAWAII), NASA/ESA/A. SIMON (GSFC) AND THE OPAL TEAM AND J. DEPASQUALE (STSC), NASA/ESA/AND C. ROBERT O'DELL (VANDERBILT UNIVERSITY)



Distorted doughnut

RELEASED: 23 MAY 2013

From Earth, the Ring Nebula (M57) looks like a simple ellipse. But combining Hubble data with previous ground-based observations shows that the nebula is actually shaped like a distorted doughnut, with a central gap shaped like a rugby ball.

► Hubble is lifted up by the Shuttle's robot arm during the second servicing mission, STS-82, dubbed 'Superbowl'

A telescope for a new millennium

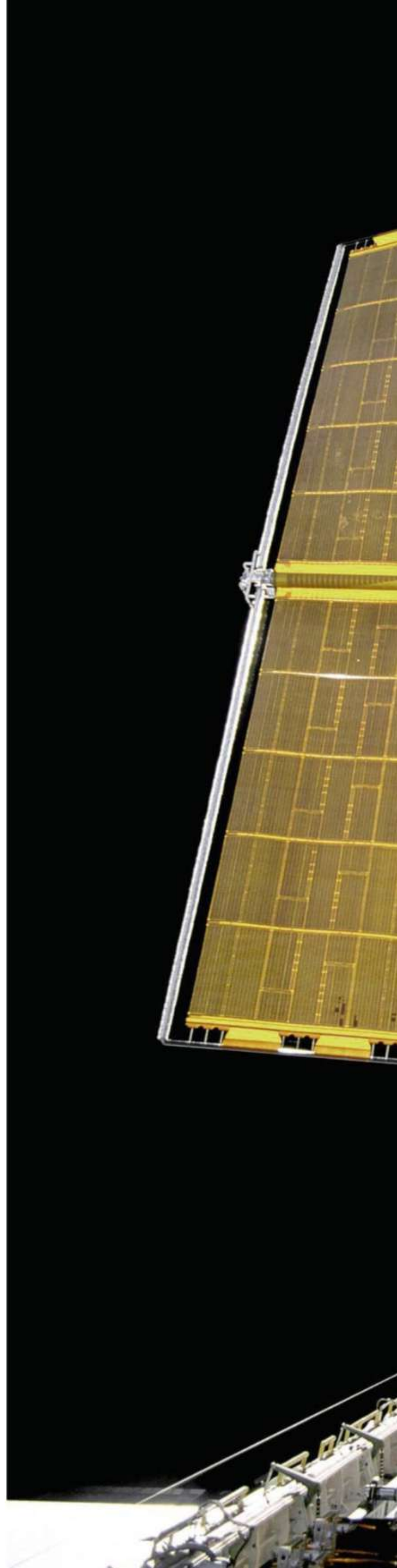
Hubble's in-built maintainability proved its saving grace, keeping it up to date with emerging technology

By Ben Evans

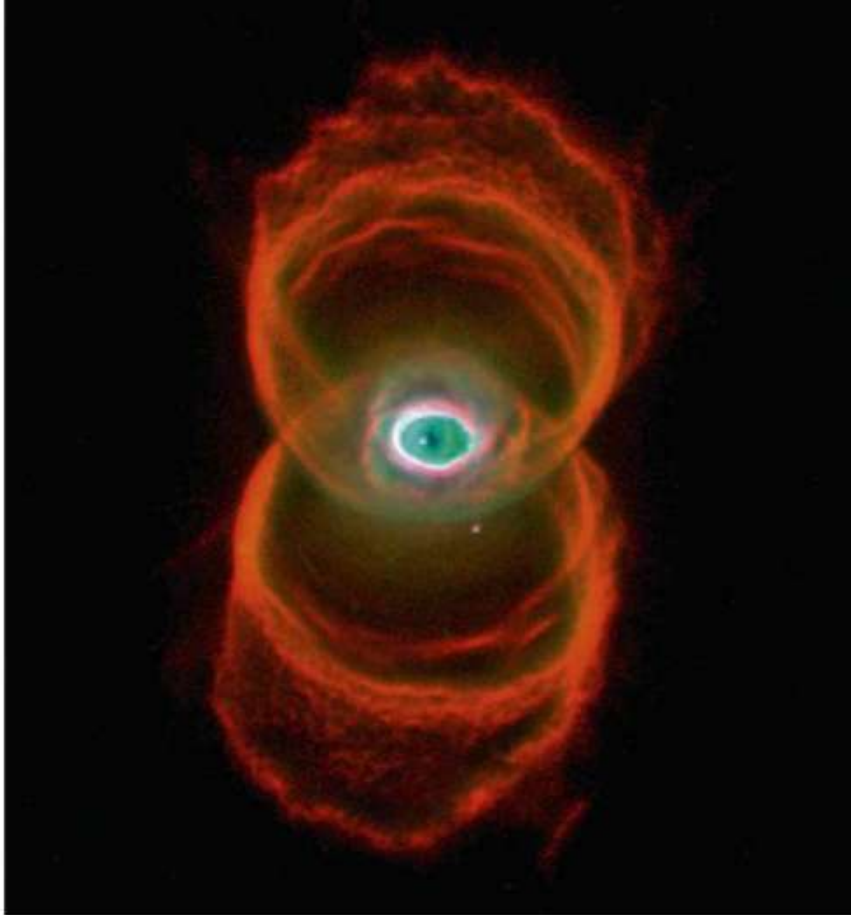
From its launch in 1990 to the departure of its last servicing crew in 2009, 32 astronauts worked on Hubble. One of them, self-confessed 'Hubble Hugger' John Grunsfeld, visited three times. They performed a total of 23 spacewalks totalling 166 hours to replace solar arrays, add scientific equipment and fit new computers and power control units. They fixed Hubble's notoriously failure-prone gyroscopes, patched its cracked and crumbling insulation and undertook intricate surgery to bring two instruments back from the dead. Those who serviced Hubble were held in high esteem by those who did not; astronaut Bob Curbeam, who never visited the telescope, was so impressed with their coolness that he called them simply 'the Jedi'.

If the STS-61 crew brought Hubble back from the brink, then the four Shuttle missions which followed turned it into a powerfully capable observatory for the new millennium. They transformed it in the eyes of the public, enabling it to seize hearts and minds as never before. "It's Americana," said Hubble spacewalker Rick Linnehan, "like cheeseburgers and Clint Eastwood." Even the alternative rock band Pearl Jam used a Hubble image of the Hourglass Nebula on the cover of their 2000 album, Binaural.

When the STS-82 astronauts arrived in February 1997, their opening spacewalk was nicknamed 'Superbowl' by program scientist Ed Weiler. It required the crew to pull out two original instruments – the GHRS, which had succumbed to an electrical failure, and the FOS – and replace them with the Space Telescope Imaging







◀ This image taken by Hubble of the Hourglass Nebula was used on one of the album covers of rock band Pearl Jam

➤ Spectrograph (STIS) from NASA's Goddard Space Flight Center in Maryland and the University of Arizona's Near-Infrared Camera and Multi-Object Spectrometer (NICMOS).

The former would provide spectroscopy of planetary atmospheres, stellar nebulae and the relationship between black holes and their host galaxies at ultraviolet, visible and near-infrared wavelengths. STIS could gather 30 times more spectral data and 500 times more spatial data than previously possible. But the infrared spectrometer, coronagraph and polarimeter that was NICMOS seemed oddly incongruous, since Hubble operated at ambient temperatures totally unsuited to heat-sensitive optics. The instrument carried a flask of nitrogen ice to cool its sensors and enable them to study exotic objects like brown dwarfs – bigger than planets, smaller than stars – which emit their radiation most strongly in the infrared.

Both more than proved their worth. STIS surveyed multiple galaxies, observed a debris disk around the star Beta Pictoris, and observed atmospheric sodium and huge quantities of hydrogen, carbon and oxygen around the exoplanet HD 209458b. Closer to home, NICMOS detected an impact crater on the asteroid Vesta and its data allowed spectroscopic measurement to be made of several exoplanets.

Tech troubles

Sadly, neither were immune to technical troubles. STIS suffered a power supply failure in 2004, but was repaired by the STS-125 crew on the final Hubble visit in May 2009. And although STIS remains fully functional today, NICMOS was less fortunate. An electrical short caused

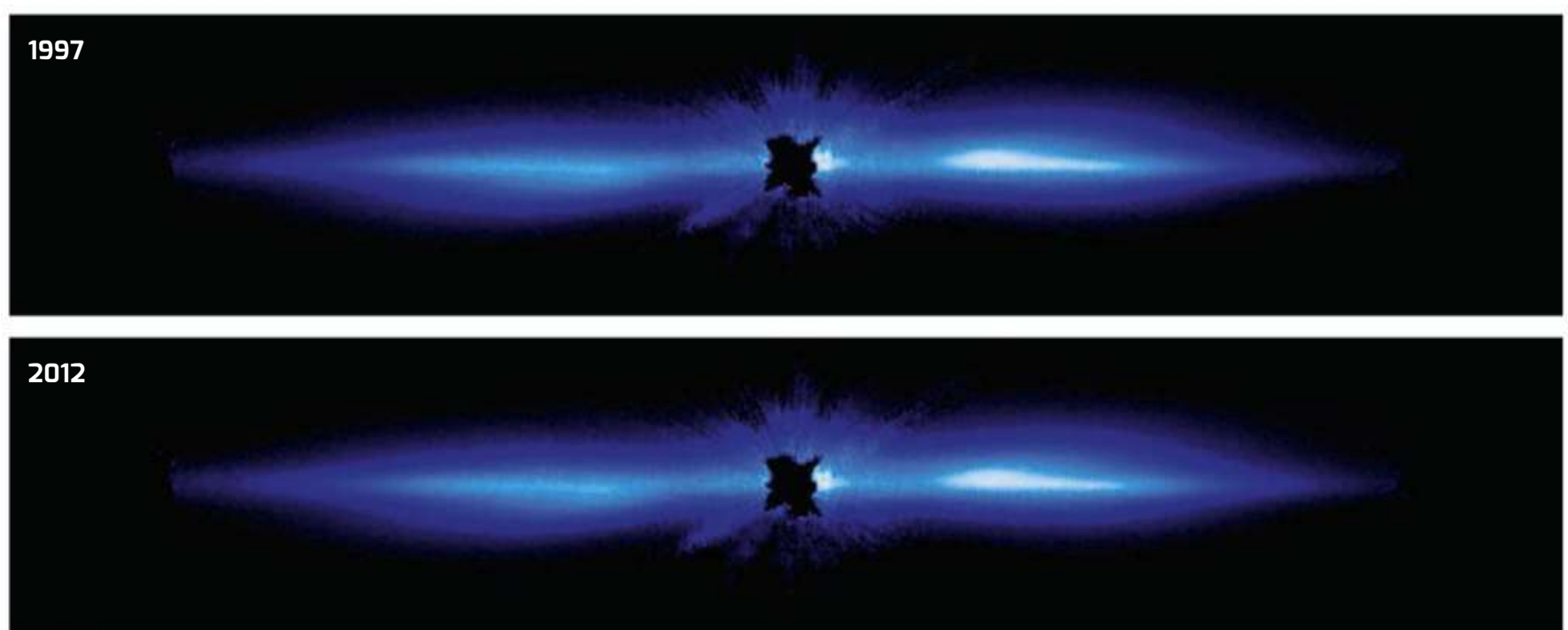
its coolant to run out in 1999. A cryocooler was fitted by the STS-109 astronauts in March 2002 and ran smoothly for six years, until

complications from a software upload and a cryogenic blockage knocked it permanently out of service.

At one stage, a six-spacewalk mission to include the removal of the last original Hubble instrument – Europe's FOC – and installation of the multi-channel Advanced Camera for Surveys (ACS) was set for mid-2000. But several gyroscope failures obliged NASA to fly an earlier-than-planned servicing call on STS-103 in December 1999. Its spacewalkers made critical repairs and swapped the telescope's vintage-1970s computer for a new model, 20 times faster and boasting six times more memory.

The ACS was finally fitted on the STS-109 mission. Built by NASA-Goddard and Johns Hopkins University, it gave Hubble a wide-field survey

“Instruments form only part of Hubble’s story. Maintaining its infrastructure and tech advancements have afforded a smooth decade of service.”



▲ Both images show the disc of debris around the star Beta Pictoris. Astronomers were surprised to find that the disc's dust distribution barely changed over 15 years, despite the fact that it orbits the star like a carousel



Astronauts C. Michael Foale (left) and Claude Nicollier on the second of three STS-103 spacewalks to replace one of the Fine Guidance Sensors

capability from visible to near-infrared and an imaging capability from near-ultraviolet to near-infrared. It has observed the most distant known quasars, found a dozen exoplanets in the Milky Way's central 'bulge' and undertaken several ultra-deep-field sky surveys. Yet it too fell foul to electrical failures in 2006-2007. Although its wide-field channel was repaired on STS-125, the high-resolution channel of ACS remains out of action.

And with the final servicing mission came Hubble's final instruments. NASA-Goddard's Wide Field Camera 3 (WFC 3) took the place of WFPC 2 to provide a far wider field of view than NICMOS. To commemorate the

telescope's 25th anniversary in 2015, it acquired a higher-resolution view of the famous Pillars of Creation image, which was taken by Hubble in 1995 of the vast 'elephant trunks' of gas and dust in the Eagle Nebula. Since each of the newer instruments has built-in corrective optics, COSTAR was now obsolete and was removed to make way for the University of Colorado at Boulder's Cosmic Origins Spectrograph (COS). This has focused on the origin of large-scale structures in the Universe, the formation of galaxies and the evolution of stellar and planetary systems.

But scientific instruments form only part of Hubble's story. Maintaining its infrastructure has been vital and

technological advancements have afforded a comparatively smooth decade of service since the departure of STS-125. Rigid solar arrays – heavier, admittedly, but also one-third smaller and producing 20 per cent greater power – replaced the wobbly original ones. They allowed all of Hubble's instruments to run simultaneously. A new power control unit helped eliminate the critical failures sustained in previous years.

Looking to the future, as Hubble has transitioned from vintage-1970s technology to modernised solid-state electronics, this enhanced reliability should ensure its continued survival throughout this decade and beyond.

Interview

Dr. Mike Massimino

Selected by NASA for the astronaut training programme in 1996, Michael J. Massimino's academic specialism focused on human-machine systems. He took part in the fourth and the final Hubble servicing mission, before leaving NASA in 2014 to continue his academic research and teach at Columbia University

“You didn't have to be extremely strong,” Mike Massimino says about spacewalking on Hubble, “but you needed to be fit.” He flew twice

to the telescope and spacewalked on it four times. “We got more and more ambitious, based on what we learned from the first missions,” he reveals. Massimino, currently senior advisor for space programs at the Intrepid Museum in New York, noted that STS-61 faced many unexpected obstacles on Hubble for the first time: from warped equipment bay doors to bent solar array masts. “They didn't have time to figure it out,” he recalls. “They were in space.”

Massimino remains convinced that later Hubble crews benefitted immeasurably from STS-61. “If you look at what we ended up doing on the later missions, the tasks were more complex than they did on the first ones, but I don't think it was any more difficult, because we had learned from what those guys had done,” he explains. “The first servicing mission was probably the most challenging. They were there to save the telescope and do these things for the first time. We were following in their footsteps.”

Back-to-back spacewalks were equally tough. “It was pretty tiring,” says Massimino. “As soon as you've done one, you have to get ready for the next one the next day, and sometimes they ran 'long'. We really had to work as a team to get it done and work well with the ground controllers as well.”



▲ Mike Massimino peers through the Shuttle's aft flight deck window during the mission's fourth spacewalk

“On the Space Station, things you didn't get done, you could come back and do them. With Hubble, you either did it or it wasn't getting done – maybe ever.”

That responsibility was a heavy weight. “It was a lot of spacewalks and you could make mistakes, but there were consequences,” Massimino cautions. “You had to be delicate. With the Space Station, you weren't encouraged to be rough, but Hubble was really delicate. You had to be mindful of where you were, what you touched, what you knocked into. You couldn't use the same method that you used on the Space Station.”

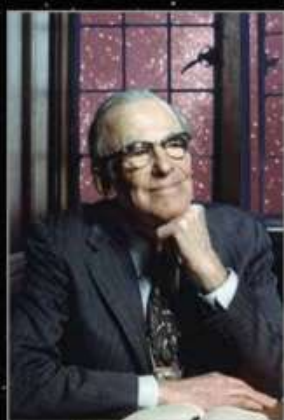
Added to that fact was the infrequency of Shuttle visits to Hubble. “On the Space Station, things you didn't get done, you could come back in a year and do them,” he says. “With Hubble, you either did it or it wasn't getting done. We would develop a new tool or technique, because the more time we could save, the more things we could do. If you didn't get it done, it wasn't going to get done on that mission – or maybe ever.”

THE SPACECRAFT: MAINTENANCE AND SERVICING



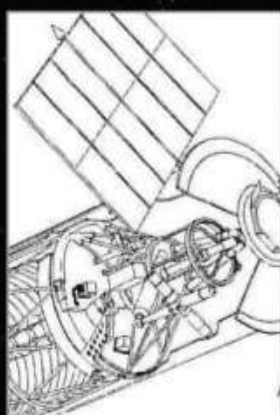
Timeline of a SPACE TELESCOPE

Key dates in Hubble's mission, from initial concept through to regular maintenance and the planned end of its life



1946

Lyman Spitzer writes about the usefulness of a space-based telescope



1972

Large Space Telescope project begins, led by NASA's Marshall Space Flight Center



esa

1977

A campaign succeeds at re-starting the project and ESA comes onboard



1981

Optics house Perkin-Elmer finishes Hubble's primary mirror, which took two years to build and polish



1986

Shuttle Challenger explodes. Shuttle fleet grounded. Hubble completes vacuum chamber test

1968

First Orbiting Astronomical Observatory launched



1974

Project cancelled due to the cost, overly ambitious nature and lack of scientific support



1978

Congress restores funding for the project. Lockheed begins building the telescope



1985

Astronauts (including Commander John Young, below) assigned to the mission to launch Hubble - STS-61J



1990

Hubble launches aboard mission STS-31. Spherical aberration discovered





1991

Ball Aerospace begins building COSTAR, whose mechanical arms would deploy mirrors to refocus light from the primary mirror before it reaches the instruments



1997

STS-82 flies second servicing mission, removes GHRS and FOS and installs STIS and NICMOS. Astronauts' opening spacewalk was nicknamed 'Superbowl'



1999

NICMOS shuts down following an electrical failure. Four of Hubble's six gyroscopes have failed by the end of the year, forcing NASA to put the telescope into safe mode for several weeks



2004

Following the Columbia Shuttle disaster, NASA cancels fifth servicing mission and lays plans for a robotic mission to Hubble. STIS suffers electrical failure



2015

To commemorate Hubble's 25th anniversary, the WFC 3 takes a higher resolution image of the Eagle Nebula than was captured in 1995

1993

STS-61 flies first servicing mission, replaces solar arrays, removes HSP and WFPC, installs COSTAR and WFPC 2



1998

NASA plans third servicing mission to Hubble, with a record-breaking six spacewalks. But this doesn't go ahead as STS-103 flies earlier than planned the following year



2002

STS-109 flies fourth servicing mission, replaces solar arrays and power control unit, removes FOC (last original Hubble instrument) and installs ACS in its place



2009

STS-125 flies fifth servicing mission, repairs STIS and ACS, fits WFC 3 and COS, and fits soft-capture mechanism for future robotic mission to take Hubble out of orbit



2028-2040

Hubble is now well equipped to function for many more years. The plan is to end its life with destructive re-entry





NASA/ESA AND THE HUBBLE HERITAGE TEAM (STSCI/AURA),
NASA/ESA, NASA/ESA/HUBBLE HERITAGE TEAM

Trick of the eye

RELEASED: 8 JUNE 2006

Titled edge-on to the view from Earth, disc galaxy NGC 5866 looks anything but like a disc. From this angle, Hubble's sharp vision has captured a line of dust splitting the galaxy in two, as well as other features such as a subtle red bulge surrounding a bright nucleus, a blue disc of stars running parallel to the dust line, and a transparent outer halo.



◀ Star burst

RELEASED:
14 NOVEMBER 2013

M15 in the constellation of Pegasus is one of the most densely packed and oldest globular star clusters in the Universe – around 12 billion years in age. Super-hot blue stars and cooler green ones surround the white core, where the stars are most densely packed. M15 has a rare type of black hole at its centre.

Bubble bomb ▶

RELEASED:
21 APRIL 2016

A shell of glowing gas expands around a star in the Milky Way. Its shape is caused by strong solar winds from a huge star (top left) sculpting the gas and dust into a bubble. Hence, the nickname for NGC 7635 – the Bubble Nebula.

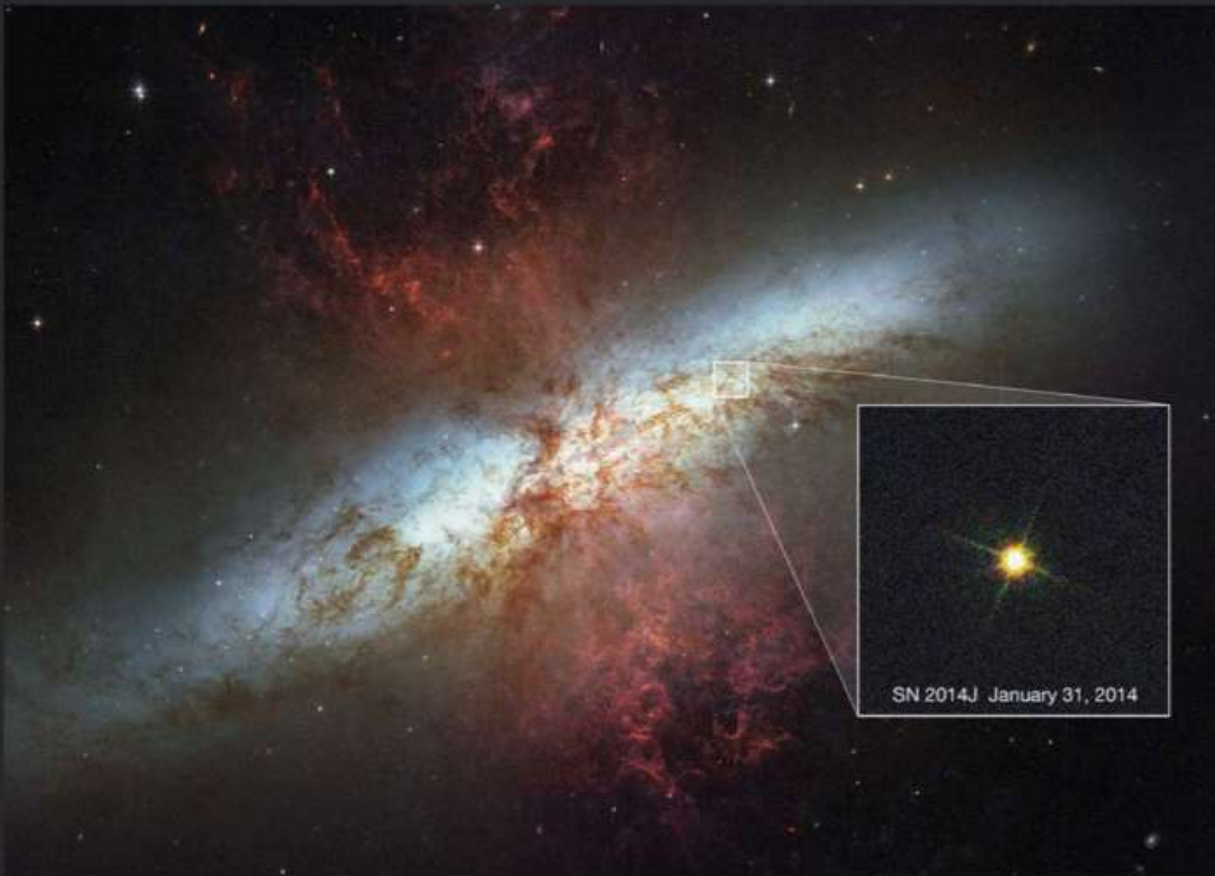




Cosmic creepy-crawly

RELEASED: 9 JANUARY 2014

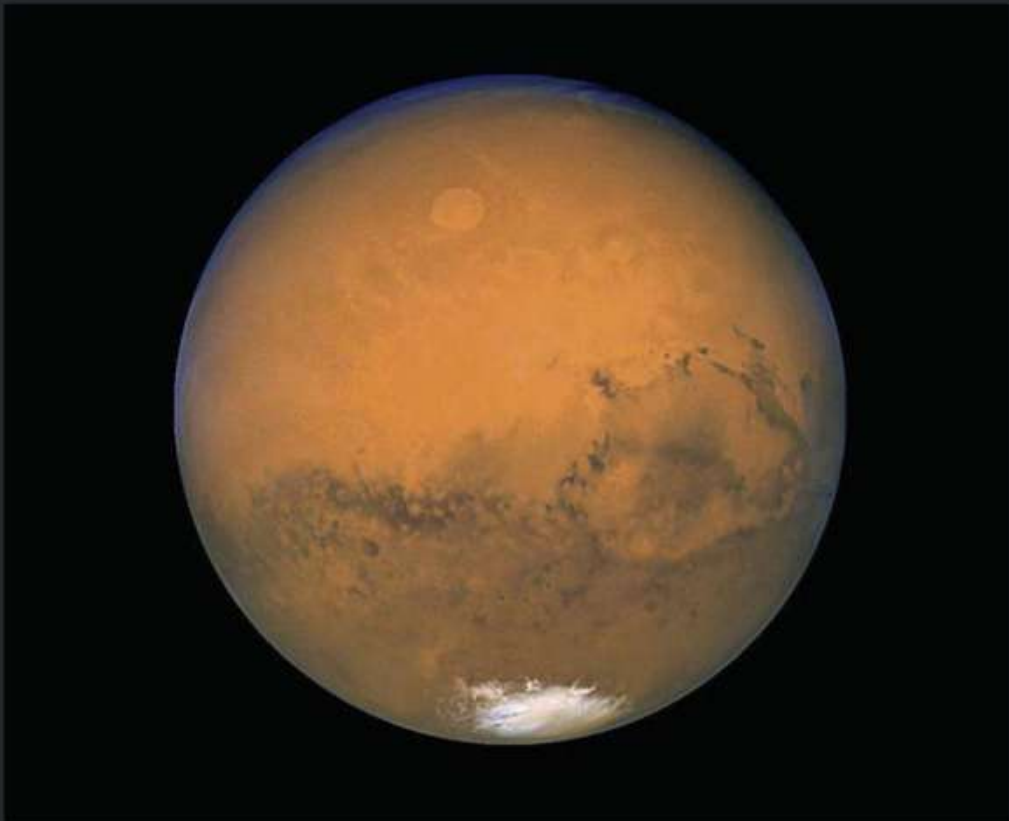
This image captures the turmoil of the Tarantula Nebula where intense radiation, stellar winds and supernova shocks from massive stars sculpt spidery filaments, glowing gas and thick dust. More than a thousand lightyears across, this vast star-forming region lies within the nearby galaxy the Large Magellanic Cloud.



▲ Celestial ruler

CAPTURED: 31 JANUARY 2014

When astronomers spotted a peculiar bright spot in the spiral galaxy M82, they asked Hubble to investigate. The bright spot was a new supernova, and not just any old supernova, but a type Ia – essential in measuring distances to understand the scale of the Universe.



▲ Mars under fire

CAPTURED: 26 AUGUST 2003

The many small, dark craters in this image reveal the numerous impacts Mars has endured over time. Near the centre of the image is the 450km-wide Huygens crater, where carbonates have been discovered, suggesting Mars once had a thicker carbon dioxide atmosphere, full of moisture.

NASA/ESA/E. SABBI (STSCI), NASA/ESA/A. GOOBAR (STOCKHOLM UNIVERSITY) AND HUBBLE HERITAGE, NASA/ESA AND THE HUBBLE HERITAGE TEAM (STSCI/AURA), NASA/ESA/J. BELL (CORNELL U.) AND M. WOLFF (SSI)

HUBBLE
SPACE TELESCOPE



THE SCIENCE

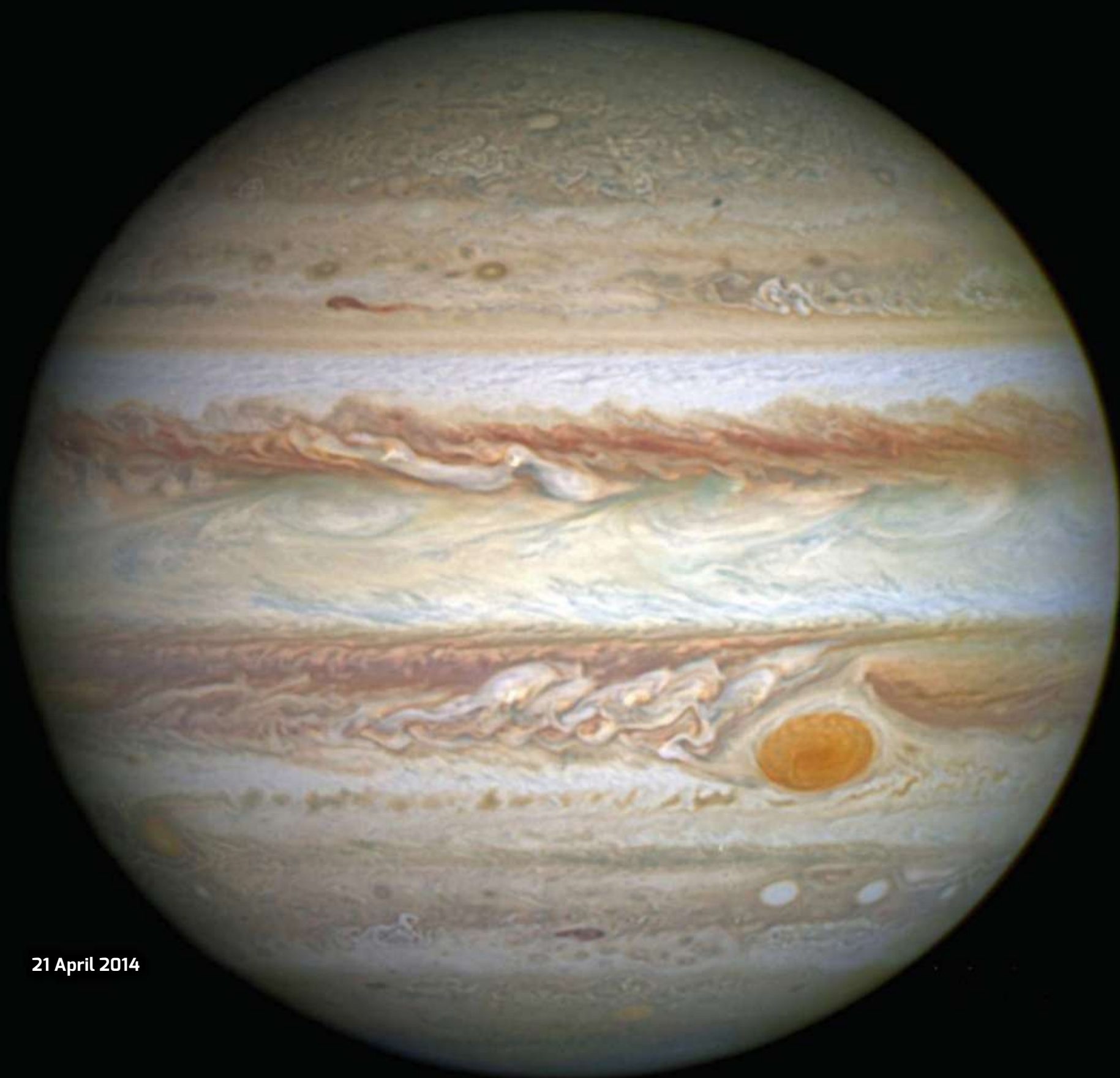
NASA/THE HUBBLE HERITAGE TEAM (AURA/STSC) AND ESA

As the 20th century began, astronomers could only dream of an observatory orbiting high above Earth's surface, searching space for cosmological secrets. Yet Hubble has done just that. It has helped to shine a light on our planetary neighbours and has discovered the existence of exoplanets – alien worlds around other stars. It has watched the birth, life and death of stars, and it has helped to bring the darkest depths of the Universe into the light. This section delves into the ground-breaking science that has been enabled by Hubble in all of these areas.



THE SCIENCE

Captured on 8 February 2004,
this image shows the distant
star V838 Monocerotis



21 April 2014



1995



2009



2014

◀ The dramatic shrinking of Jupiter's Great Red Spot is captured in 1995, 2009 and 2014

A new perspective on THE PLANETS

For 30 years, Hubble has revealed secrets about neighbouring worlds, improving the science done by other planetary probes

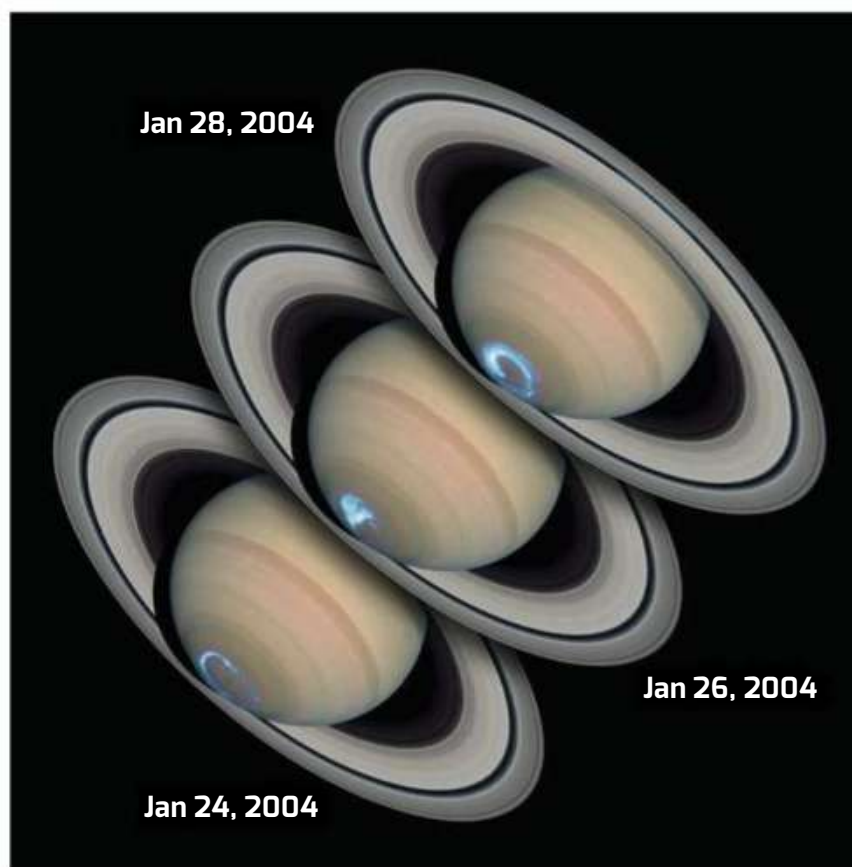
By Elizabeth Pearson

The Solar System is our cosmic back garden. It should be one of the best-known parts of our corner of the Universe.

Yet when Hubble launched in 1990 our planetary neighbourhood was still deeply shrouded in mystery. Looking up from Earth, the ever-shifting atmosphere blurred our view of the planets, making it difficult to see their features. Above the turbulent air, Hubble could watch these worlds in peace and has been doing so for the last three decades.

This long life has been one of Hubble's greatest assets, making it possible to reveal the weather and climate patterns of changing seasons on our sister worlds as they make their journeys around the Sun. The Hubble science team have taken advantage of this unique long view by undertaking a project called the Outer Planet Atmospheres Legacy (OPAL).

"OPAL employs Hubble to look every few months at Jupiter, Saturn, Uranus and Neptune to see if they've changed,"



▲ These images reveal how much Saturn's aurorae change in the space of just a few days

says Jennifer Wiseman, Hubble's senior project scientist. "Through OPAL we've learned how the Great Red Spot on Jupiter, a giant storm, is actually shrinking and changing colour over time. We see new storms cropping up, and we see them coming and going on some of the other outer planets too. Studying the changing nature of the

planets in our Solar System is something that Hubble is enabling us to do through both its clarity of imagery and its longevity."

Mission support

Of course, Hubble hasn't been the only one watching the planets over the years. Since its launch, dozens of missions have been sent across our Solar System and Hubble is often called upon to supply much needed context. When Cassini arrived at Saturn in 2004, it could only see small parts of the planet at a time. Hubble, however, was able to take in the entire planet. While

this was at a much lower resolution, the telescope was able to track storms and auroral activity to help planetary scientists understand the data Cassini was sending back.

"This profoundly improves the science return from any of these particular missions, compared to them operating on their own," says Wiseman.

Mars has been another target of Hubble's attentions as it works in concert with the armada of spacecraft on and around the Red Planet. The

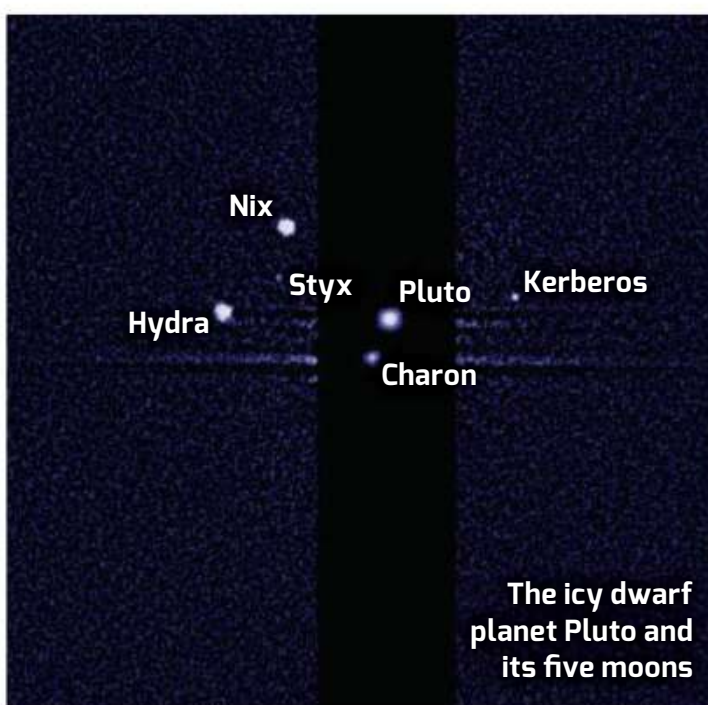




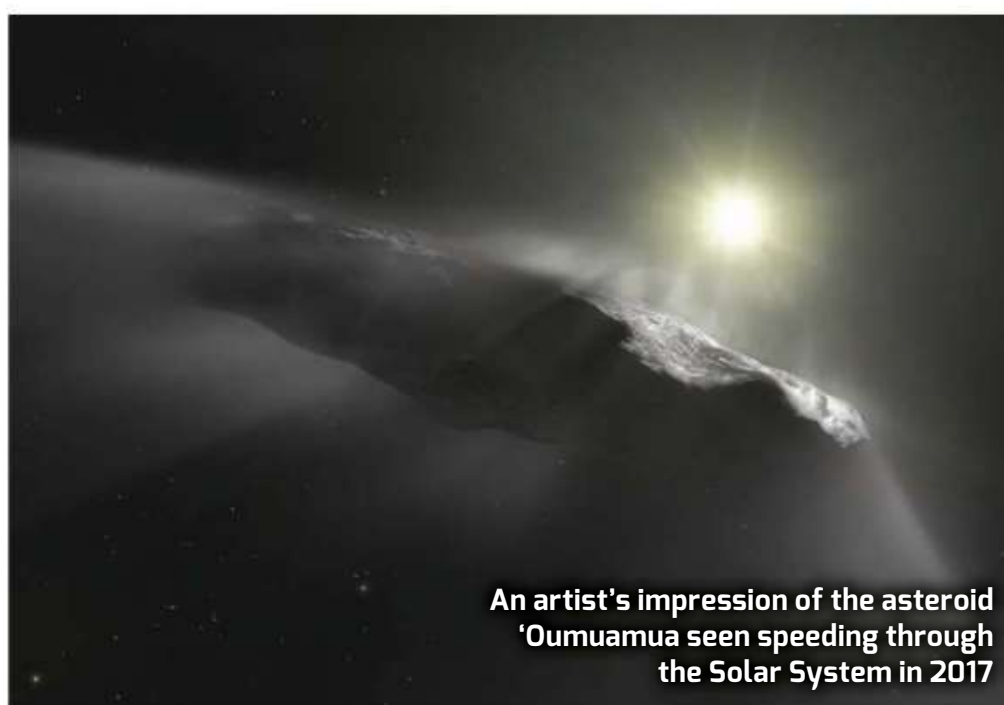
A dust storm brews on Mars in the Hellas Basin (bottom right)



Impact sites from comet Shoemaker-Levy 9 strewn across the surface of Jupiter



The icy dwarf planet Pluto and its five moons



An artist's impression of the asteroid 'Oumuamua seen speeding through the Solar System in 2017

“When Hubble observed some of Jupiter’s moons, both Ganymede and Europa showed signs of liquid water oceans”

➤ telescope has helped to track the huge dust storms which blow across the planet every Martian year. Once again, this gives a global appraisal of the storm’s progress while the *in-situ* probes note localised changes such as temperature and pressure.

It’s not just during missions that Hubble offers support, however. For almost every planetary mission of the last 30 years, Hubble has been used to scout the way before the spacecraft even reached its target.

“Hubble was used to help in planning the New Horizons mission which passed by the Pluto system in 2015,”

says Wiseman. “The space telescope’s observations helped inform the planning of that probe’s trajectory and get it safely to Pluto.”

Eye in the sky

Before New Horizons’ approach, the operations team feared flying into an unseen moon or other obstacle around the dwarf planet, and so used Hubble to search for potential hazards. It was during this campaign that Hubble revealed the presence of a pair of moons, Nix and Styx, allowing New Horizons to plot a trajectory which avoided them.

Hubble offers another perspective that many of these planetary spacecraft lack – the ability to observe in the infrared and ultraviolet. For the Juno mission at Jupiter this capability provides extra resolution to its observations of the gas giant’s magnetic field. Juno’s instrument payload cannot register the high-energy, ultraviolet aurorae these fields create but Hubble can. By combining the two, astronomers are given a far more complete view of the planet, allowing them to work out even more detail about the magnetic fields of this giant world.

“We’ve also used Hubble to study the nature of some of the moons of these planets, and we’ve revealed some quite unexpected results,” says Wiseman. “For example, when Hubble observed some of the moons of Jupiter, we found that both Ganymede and Europa

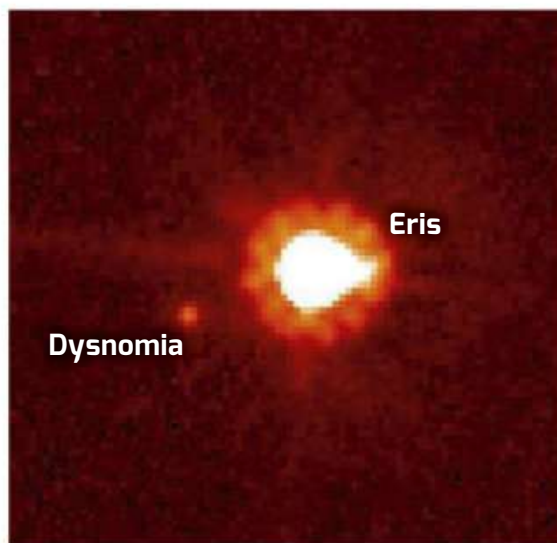
Top 3 Solar System moments

Hubble has made some of the most definitive planetary discoveries in recent times



Seasons on Uranus

With no long-term orbiter to keep watch over the outermost planets Uranus and Neptune, Hubble has been key in tracking their changing seasons. When Voyager 2 flew past Uranus in 1986, the ice giant appeared to be a placid marble with little weather. But Hubble has revealed the planet is now in a more active phase, suggesting that seasons have changed, and shown several dark patches believed to be great storms blowing up on the planet.



Demoting Pluto

In 2005, Caltech astronomer Mike Brown uncovered a large body in the outer Kuiper Belt, now known as Eris. After a closer look with Hubble he was able to measure the world's diameter. It was over 2,300km wide, making it around the same size as Pluto. The discovery triggered a debate in the astronomical community over what the definition of a planet should be, an argument that ultimately led to Pluto being demoted to dwarf planet.



Jupiter's aurorae

When Hubble first launched, it couldn't get a good look at Jupiter's ultraviolet aurorae. Its cameras took so long to take a picture that Jupiter's rapid spin blurred the image. Then in 1997, Hubble was upgraded with the much more sensitive Space Telescope Imaging Spectrograph. This could take pictures fast enough to reveal an aurora's shape and found it formed curtains just like Earth's, extending several hundred kilometres over the surface.

showed signs of liquid water oceans under an ice-crust outer layer."

In 2016, Hubble helped to confirm the presence of water outside the moons as well, when it confirmed there was a plume of water ice fountaining high over Europa, forced up from an underwater ocean through the cracks in the moon's crust.

"Those observations are still taking place, still being studied and are still somewhat controversial," says Wiseman. "But that's the exciting thing about being on the cutting-edge of science, doing and redoing these observations, reanalysing them and working out exactly what it is we're seeing."

Initiatives like these are laid out long in advance, but not all of Hubble's work is planned out so far ahead. Some of its greatest triumphs have come from those times when the Solar System

threw out something unexpected – those events which make astronomers drop whatever they're doing and race to the nearest telescope. When those events come along, Hubble is always in demand.

Interstellar visitors

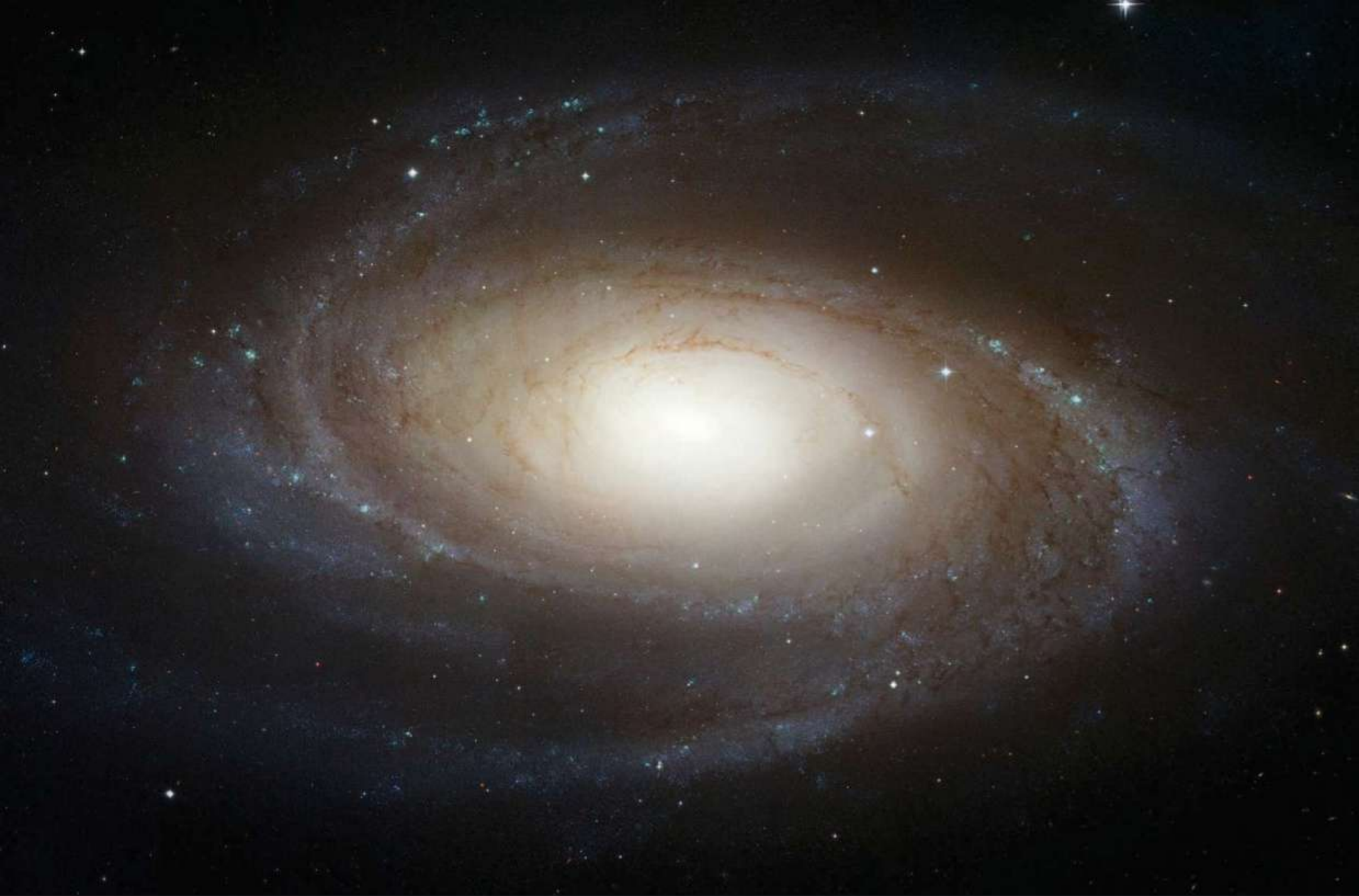
"One of Hubble's most famous detections happened early on in its career, when comet Shoemaker-Levy 9 unexpectedly collided with Jupiter in 1994," says Wiseman. As soon as astronomers realised the comet would collide, they called on the Hubble team to make sure the telescope was watching.

"That incredible set of images completely transformed our understanding of how dynamic the Solar System is," says Wiseman. "We realised how vulnerable planets actually are to being impacted by

objects and debris whizzing around."

Hubble has observed many comets and asteroids since then, but in the last few years a new category of transient space rock has been added to the line-up – interstellar visitors. In 2017, asteroid 'Oumuamua was seen speeding through our Solar System, having been thrown out of another star system. Then in late 2019, comet 2I/Borisov followed suit. In both cases, Hubble was on hand to capture the objects on camera as they flew by.

Since Hubble launched in 1990 it has revolutionised our knowledge of the worlds in our back garden. The telescope has been a key tool in helping to unravel their mysteries, but there are still plenty of secrets hidden in the shadows of these distant worlds. As long as it's still running, astronomers will be calling on Hubble to help drag them into the light.



▲ Grand designs

RELEASED: 28 MAY 2007

This image of M81 is one of the best examples of a grand design spiral galaxy, where the arms are prominent and well-defined, and wind all the way down into the core of the galaxy.

Reflection nebula ►

RELEASED: 2 MARCH 2000

A matter of weeks after astronauts carried out repairs on Hubble in December 1999, the space telescope captured this image of reflection nebula NGC 1999. Reflection nebulae are clouds of interstellar dust which can reflect the light of a nearby star or stars.



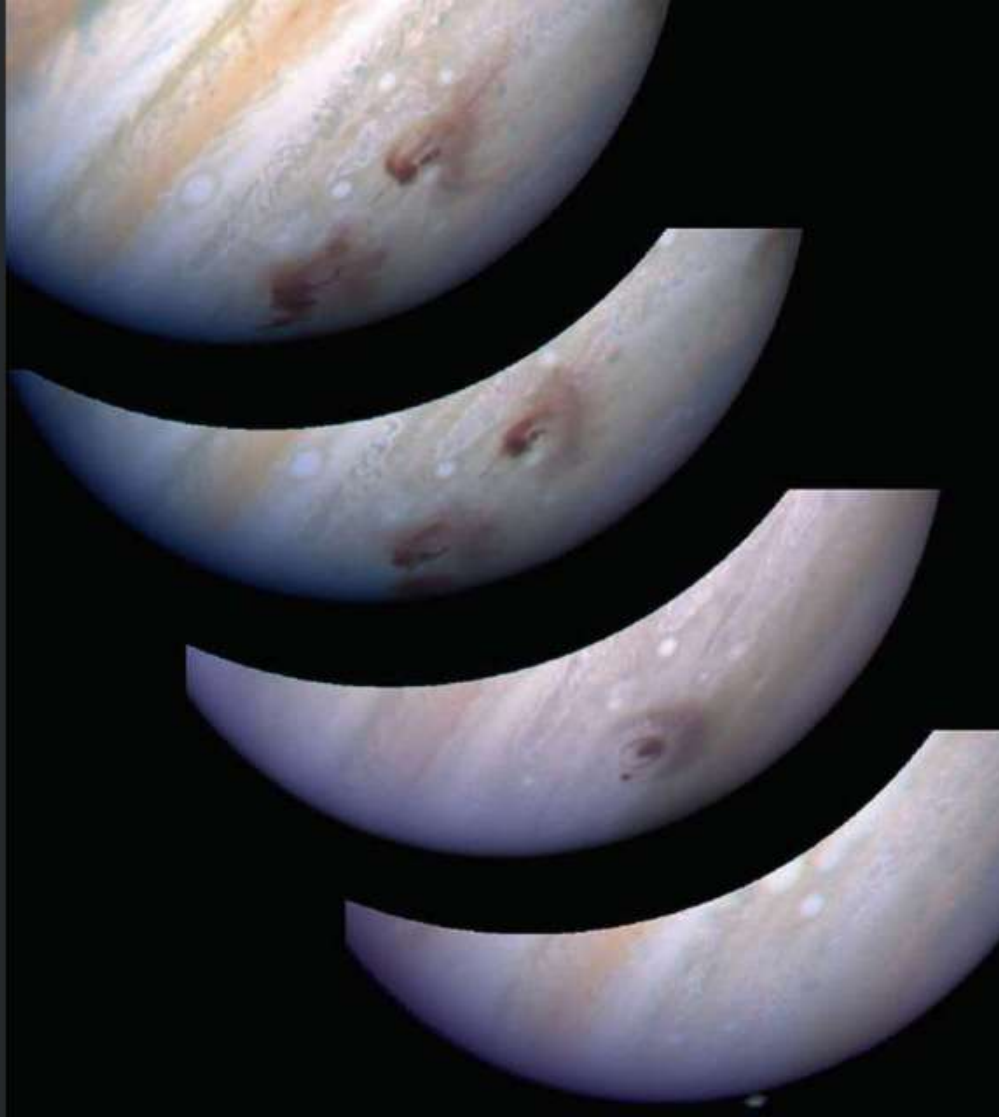
Rising eagle

CAPTURED:
NOVEMBER 2004

A billowing tower of cold gas and dust rises from the stellar nursery of the Eagle Nebula. At 9.5 lightyears tall, its height is about twice the distance from our Sun to the next nearest star.

NASA/ESA AND THE HUBBLE HERITAGE TEAM (STSCI/AURA X 2,
NASA/ESA AND THE HUBBLE HERITAGE TEAM (STSCI)





◀ Comet collision

CAPTURED: JULY 1994

Hubble captures chunks of comet Shoemaker-Levy 9, which had broken apart a year earlier, crashing into Jupiter. The bottom image was taken minutes after the collision where nothing can be seen. But within two hours, a plume of dark debris is visible, and then a few days later two impact sites can be seen. The final shot shows three impact sites.

◀ Bursting into life

RELEASED: 2 OCTOBER 2007

The nebula NGC 3603 in the Carina spiral arm of the Milky Way is about 20,000 lightyears away. It burst into life in a rush of star formation around a million years ago. The stars glowing blue in the core are so hot that they are carving out a huge cavity in the gas, visible to the right of the cluster.

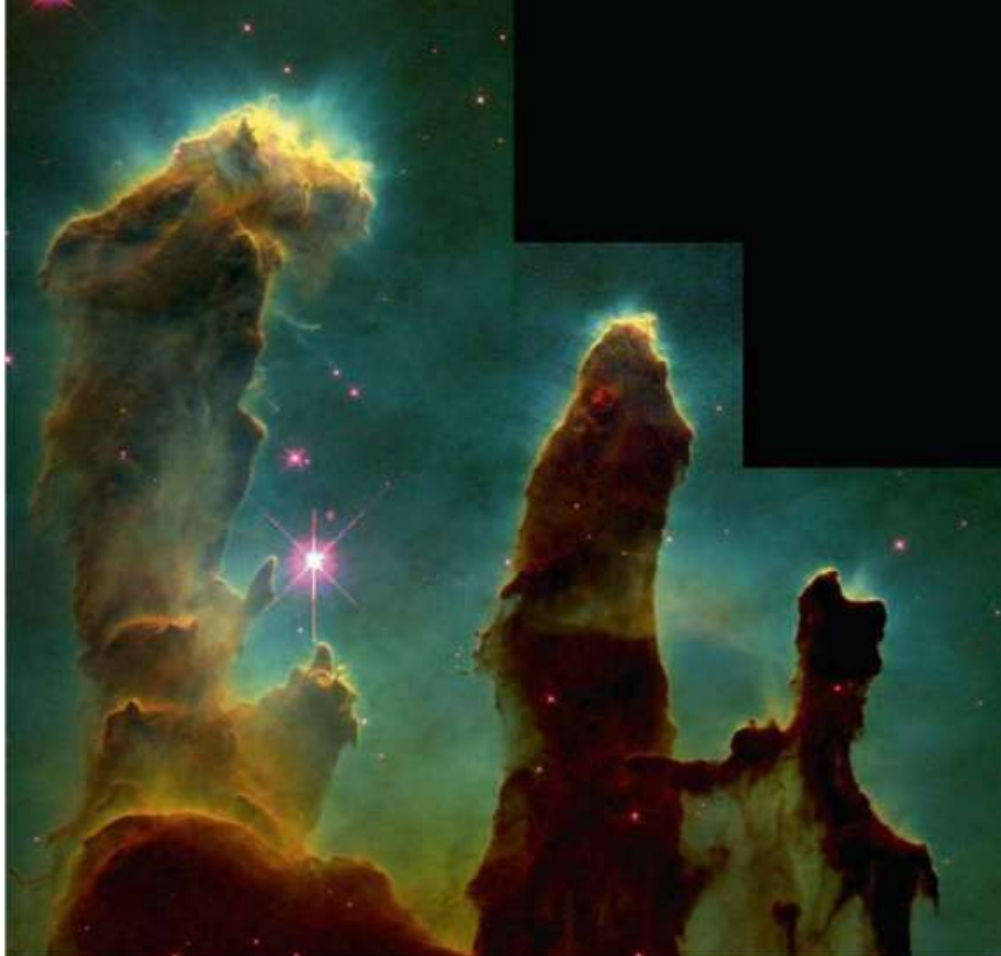


▲ What a cracker!

RELEASED: 6 JUNE 2011

This striking image is of a star in nebula IRAS 13208-6020 firing out gas and dust. The relatively short-lived phenomenon gave astronomers the chance to watch the early stages of planetary nebula formation. The term 'planetary nebula' is a misnomer, as it has nothing to do with planets. It was coined by William Herschel, when he discovered the planet Uranus, as he thought that they resembled the icy planet.

NASA/ESA AND THE HUBBLE HERITAGE (STSC/AURA)-ESA/HUBBLE COLLABORATION, R. EVANS/J. TRAUGER, H. HAMMEL AND THE HST COMET SCIENCE TEAM AND NASA/ESA, ESA/HUBBLE & NASA



▲ The Pillars of Creation in the Eagle Nebula, as captured by Hubble in 1995. The picture is composed of 32 different images from four separate cameras in the Wide Field and Planetary Camera 2

The Milky Way

The story of stars has been written across our Galaxy, and Hubble can read it

By Elizabeth Pearson

The Milky Way is home to some incredible sights. From the dusty beauty of stellar nurseries to the colourful detritus left after a star explodes, Hubble has helped to reveal the beauty of our Galaxy. Yet these images are not only stunning to look at. To an astronomer's eye, these photographs have a story to tell – the story of a star's life.

The tale begins soon after Hubble launched 30 years ago, when it first turned its eye towards some of the clouds of dust dotted throughout our Galaxy. Astronomers believed that these were stellar nurseries, the places where every star in our night sky began its life. The most famous image of one of these birthing grounds (and perhaps Hubble's most famous shot ever) is of

the Eagle Nebula, M16. The picture, taken in 1995, is better known as the Pillars of Creation, due to the dusty columns rising up through the image, inside which new stars are beginning to form.

"We see these pillar-like structures in many Hubble observations of these nebulae," says Jennifer Wiseman, Hubble's senior project scientist. "The wind from massive newly formed stars carves out these structures around the bigger clumps in the gas that is left behind."

By studying the shapes of these cloud formations, astronomers were able to unpick these critical early stages in a star's life. Partly, they've done this by watching how the clouds have changed over the last 20 years. In 2015, a new version of the same image revealed one of the jets within the

cloud had grown by almost 100 billion km, demonstrating just how dynamic these regions truly are.

The space telescope has also managed to pin down several protostars themselves. These infant stars on the cusp of forming are normally blocked from view by the very clouds of dust they grow from. Hubble's infrared camera was able to peer through this dust, however, and found several hotspots within the stellar nurseries, thought to be protostars.

Even more excitingly, when Hubble took a closer look at some of the Orion Nebula's infant stars it found several of them had discs of swirling dust – a sign they were entering the next chapter in the story of their lives and forming planets. As a star grows, it often forms a protoplanetary disc of dust around it. Over time this debris clumps together, ↘



THE SCIENCE: THE MILKY WAY

This image of the Pillars of Creation in the Eagle Nebula was taken by Hubble's newer Wide Field Camera 3 in 2014. To give an idea of scale, the towering pillars are about 5 lightyears tall

Top 3 discoveries in the Milky Way

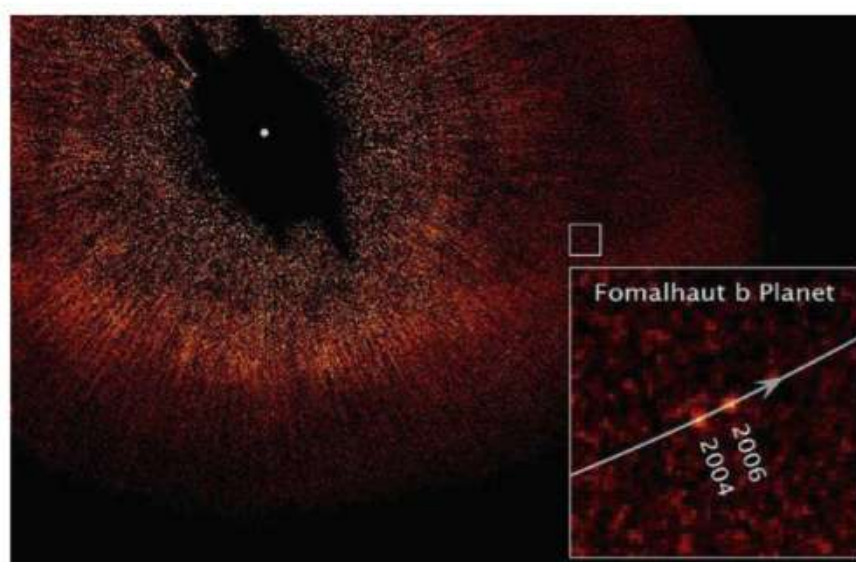


V838 Monocerotis

In 2002, the red star V838 Monocerotis flared up, temporarily shining 600,000 times brighter than the Sun. To this day, no one is sure why, but over the last 20 years the light from this flash has advanced outwards, illuminating the surrounding gas. Hubble has watched this 'light echo' expanding outwards, allowing astronomers to map out the gas around the star, hoping to find clues to what caused the outburst.

Water in the habitable zone

Astronomers have found many exoplanets in the so-called 'habitable zone' – the region around a star where temperatures allow liquid water to pool on the surface, potentially allowing life to evolve. However, there was no evidence that these planets actually contained water until 2019 when Hubble was able to discover water vapour in the atmosphere above exoplanet K2-18b for the first time.



First direct image of a planet

In 2004, Hubble took an image of the 34.5 billion km diameter disc of dust surrounding the star Fomalhaut. The inner edge of this disc has a sharp edge, suggesting it is being shepherded by a planet. Over the years, Hubble kept an eye on the system, watching a bright point of light move around the star. It was an orbiting alien world – the first ever to have been imaged directly.

- gradually growing in size to eventually become a planetary system.

Observing alien worlds

Studying these discs is a vital step in one of the fastest growing study areas of astronomy: exoplanets, the planets around other stars.

"When Hubble was designed there was no concept that it would be used to study planets outside our Solar System. We didn't know of exoplanets at that time," says Wiseman.

Since the first exoplanets were discovered back in the 1990s, over 4,000 worlds have been confirmed; a number which grows every day. Tracking these planets down requires looking at large areas of sky for a long

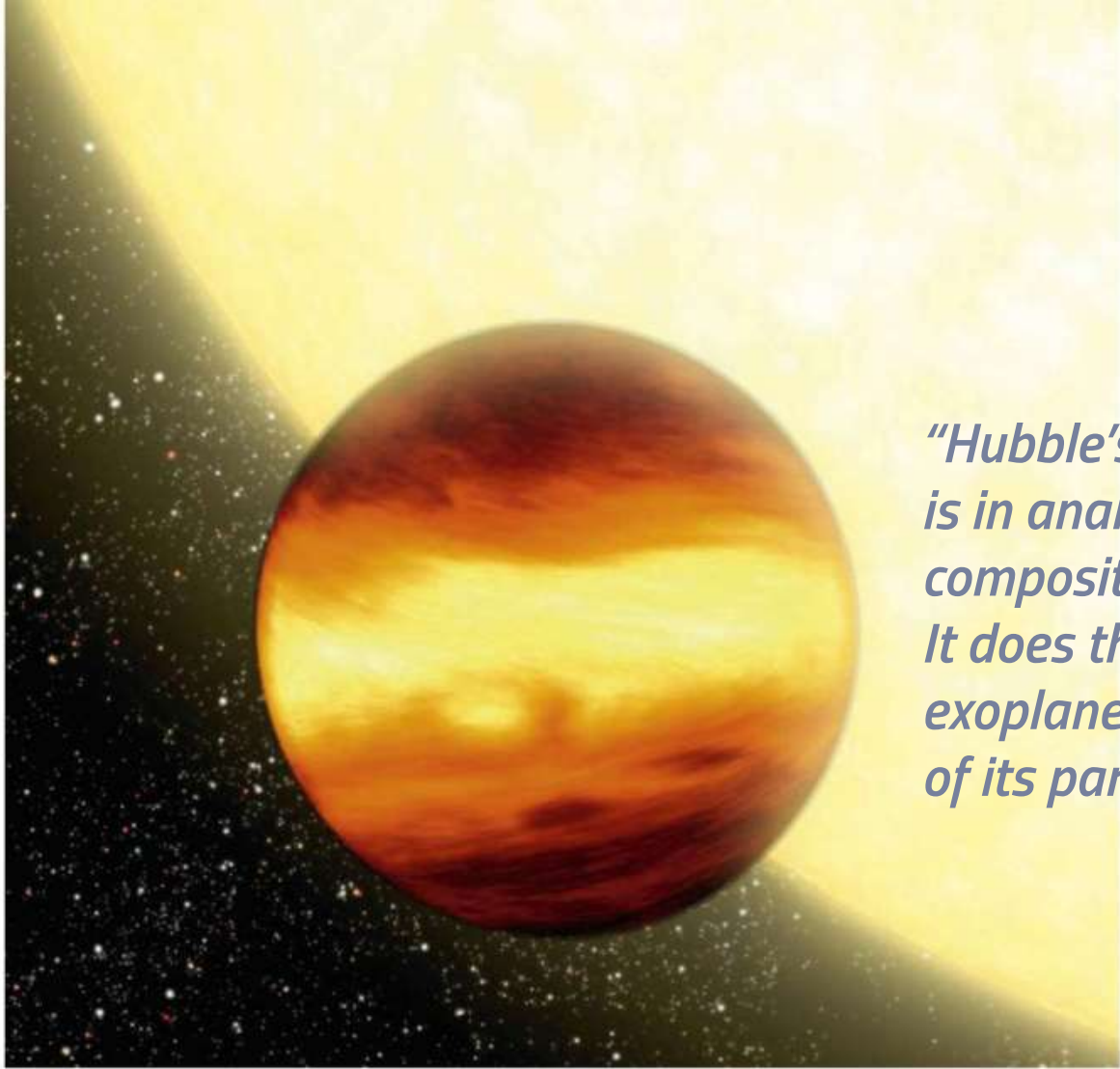
time. With its narrow field of view and the high-demand for its time, Hubble is ill equipped for this task. But it can take a deeper look at planets other observatories have already discovered.

"Hubble's pioneering contribution is in analysing the atmospheric composition of these exoplanets," says Wiseman. "It does this by looking at an exoplanet as it passes in front of its parent star. During that transit, light from the star passes through the outer regions of the atmosphere. Some of that light is absorbed by the atmosphere of that planet and that signature is still in the light received by Hubble."

By pulling this signature apart astronomers are able to detect several key elements and molecules within a

planet's atmosphere. One important molecule that Hubble is especially suited to look for is water. On Earth, wherever you find water you find life. So astronomers are keen to pin down how many other planets are as wet as ours in the hope of predicting where else in our Galaxy we might find life.

Hubble's resolution is so great that it can even create a basic outline of the weather patterns on a planet's surface. When the telescope looked at tidally locked WASP-43b, where one side of the planet always faces its sun, it was able to pick out the hot patches on its eternally sunlit side. Using this, astronomers were able to predict how the winds of the planet blow between the day and night sides.



“Hubble’s pioneering contribution is in analysing the atmospheric composition of these exoplanets. It does this by looking at an exoplanet as it passes in front of its parent star.”

But just as Hubble reveals the origins of stars and planets, it has also turned to the pages of their final act. When a star’s nuclear fuel is expended, they die. If the star is large enough, this death is an explosive affair known as a supernova. Once again, Hubble’s power lies not in first detecting these cosmic flashes but in taking a look at them afterwards.

Supernova studies

Throughout their lifetimes, stars transform the hydrogen created in the Big Bang into helium and other heavier elements. When the star goes

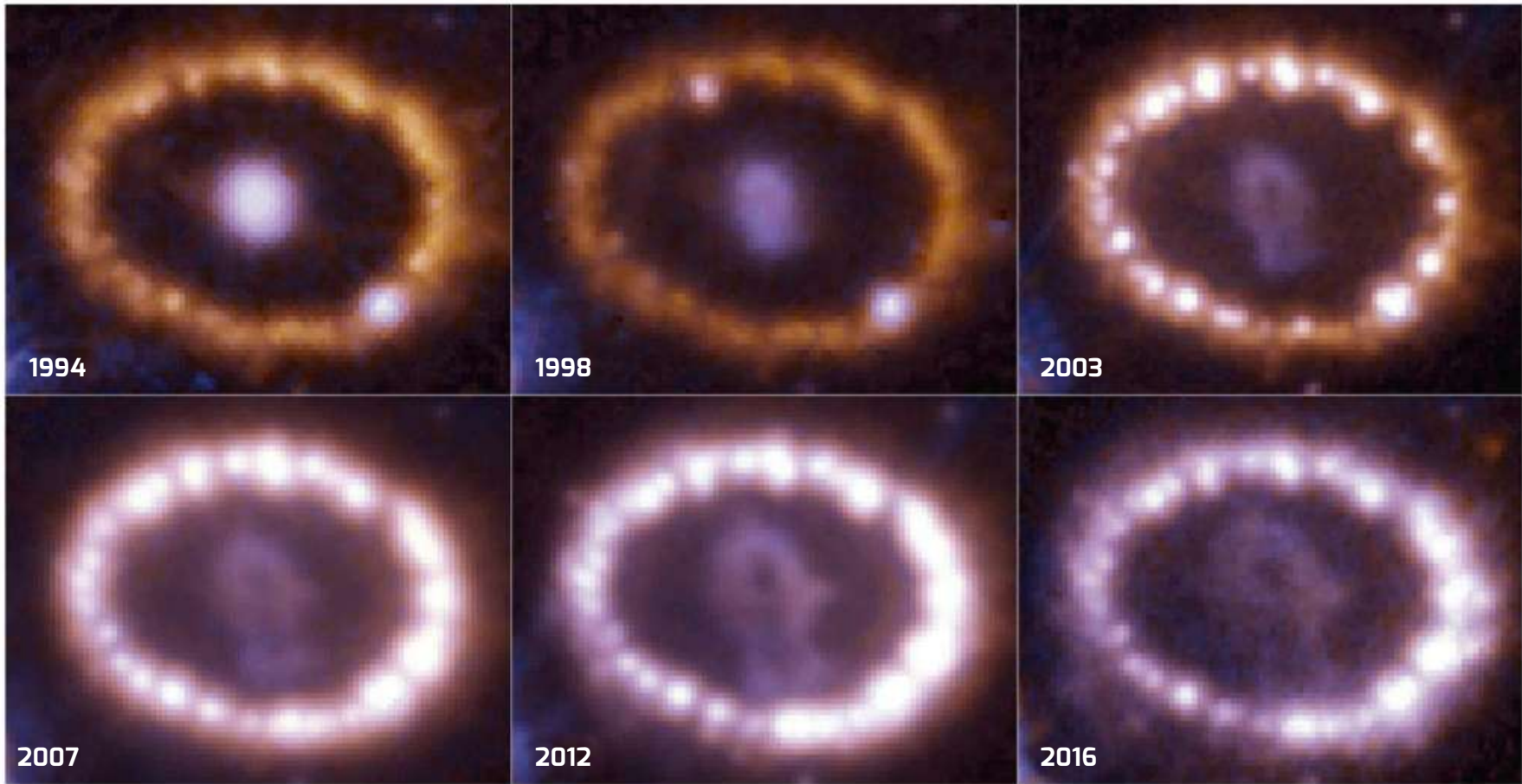
supernova, it throws these elements outward. As the hot cloud of gas crashes into the surrounding medium it creates an advancing shockwave, lit from within by a white dwarf – a small hot star, all that remains of the exploded stellar body. As these gas bubbles look fuzzy and spherical from Earth, they were initially mistaken for planets, leading them to be called ‘planetary nebula’, despite having nothing to do with planets.

In 1987, just before Hubble launched, a supernova detonated in the Milky Way’s companion galaxy, the Large Magellanic Cloud. Over the years,

Hubble has watched as the ring of gas from this explosion has moved out and expanded into the interstellar medium – the gas which fills the space between the stars.

The turbulence caused by these shockwaves can, in time, cause the interstellar medium to gather together. This new cloud, enriched with all the elements the dying star threw out into the Universe, then goes on to form stellar nurseries, bringing the cosmic tale of stellar life back around to its beginning again.

The Milky Way is a dynamic place, filled with stars being born, forming planets and then dying, only for their remains to provide the fuel to repeat the cycle again. And Hubble has been critical to observing every step of this incredible process.



▲ The evolution of the supernova 1987A between 1994 and 2016, as captured by Hubble

NASA/THE HUBBLE HERITAGE TEAM (AURA/STSCI) AND ESA, ESA/HUBBLE, M. KORNMESSER, NASA/ESA AND P. KALAS (UNIVERSITY OF CALIFORNIA/BERKELEY), NASA/JPL-CALTECH, NASA/ESA AND R. KIRSHNER (HARVARD-SMITHSONIAN CENTER FOR ASTROPHYSICS AND GORDON AND BETTY MOORE FOUNDATION) AND P. CHALLIS (HARVARD-SMITHSONIAN CENTER FOR ASTROPHYSICS)



▲ Galactic neighbour

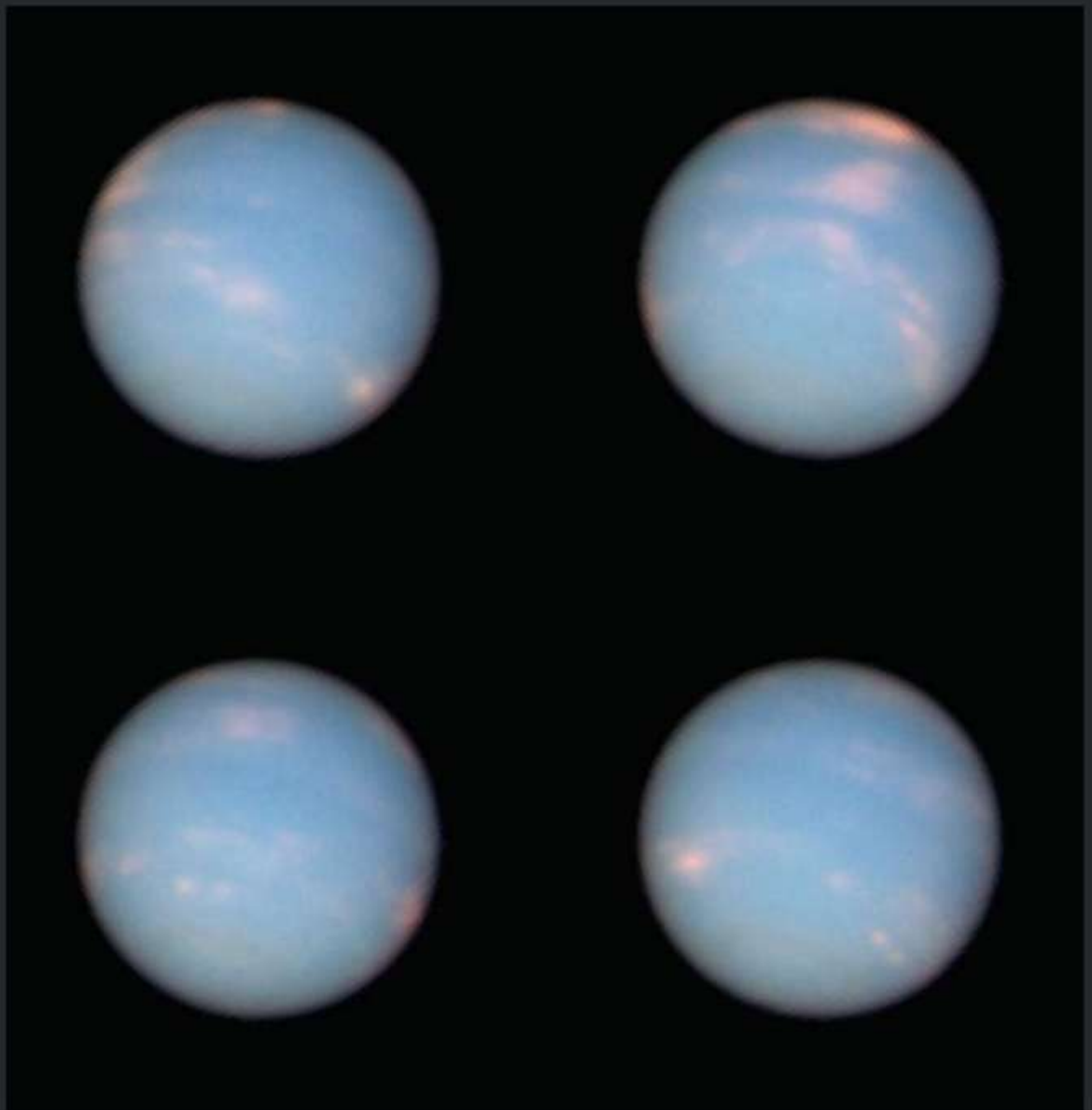
RELEASED: 5 JANUARY 2015

This is a crop of the largest and sharpest shot ever taken of Andromeda (M31) – the nearest galaxy to our Milky Way. The whole image showcased over 100 million stars and thousands of star clusters, which would require more than 600 HD TV screens to display.

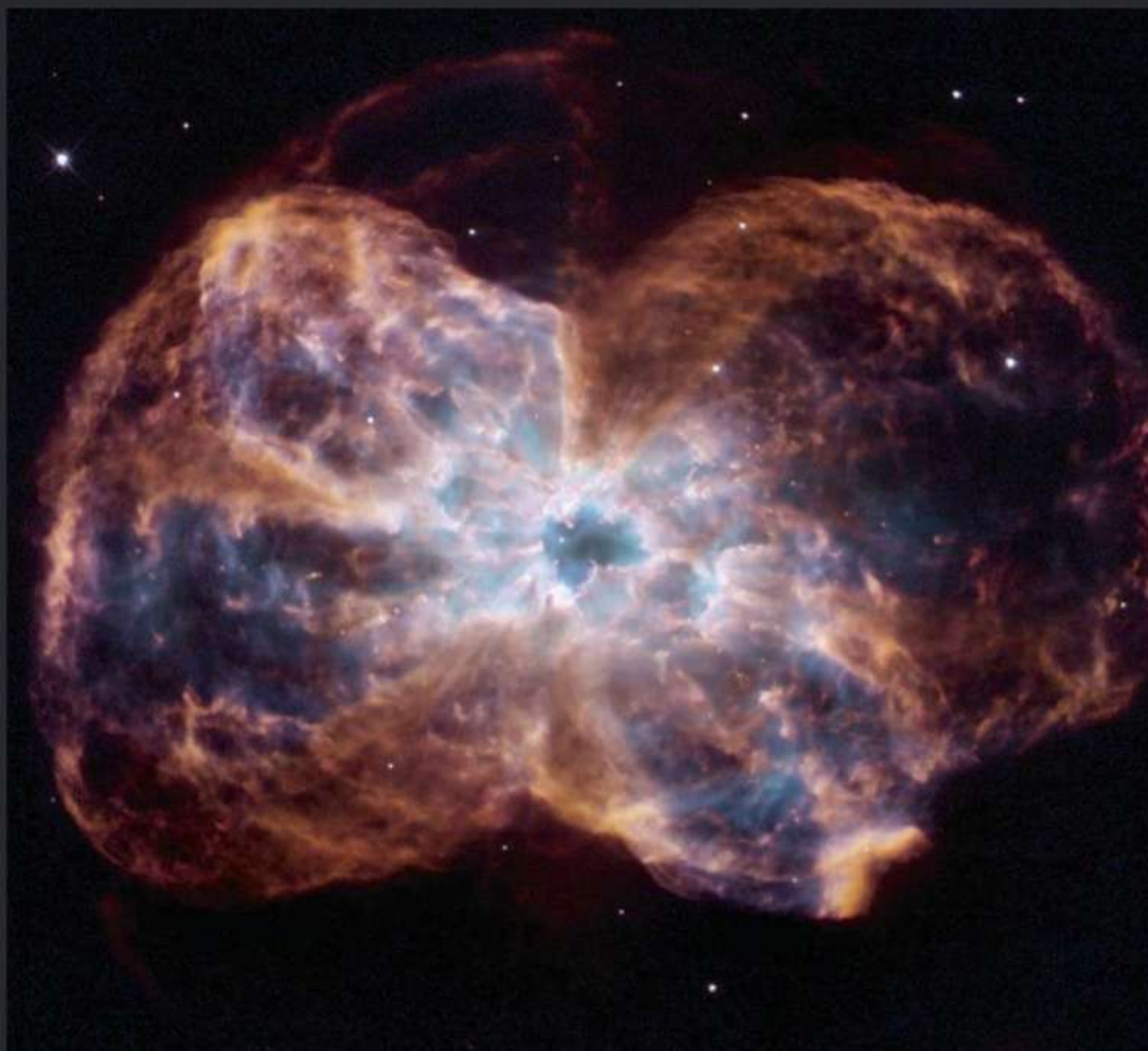
Happy birthday Neptune! ➤

RELEASED: 12 JULY 2011

To celebrate the first complete orbit of the planet since its discovery, Hubble snapped these shots of the ice giant. Neptune is the only planet in our Solar System not visible to the naked eye.



NASA/ESA/J. DALCANTON (UNIVERSITY OF WASHINGTON/USA), B. F. WILLIAMS (UNIVERSITY OF WASHINGTON/USA), L. C. JOHNSON (UNIVERSITY OF WASHINGTON/USA) THE PHAT TEAM AND R. GENDLER, NASA/ESA AND THE HUBBLE HERITAGE TEAM (STSCI/AURA), NASA/ESA AND K. NOLL (STSCI)



◀ Stellar death

RELEASED: 13 FEBRUARY
2007

This image of NGC 2440 shows what our Sun will look like in its last death throes. As the star casts off its outer gaseous layers, UV light makes the material glow. At the centre is the very hot and dense remnants of the star, known as a white dwarf.

NASA/ESA/E. SABBI (STSCI), NASA/ESA/A. GOOBAR (STOCKHOLM UNIVERSITY) AND HUBBLE
HERITAGE, NASA/ESA AND THE HUBBLE HERITAGE TEAM (STSCI/AURA), NASA/ESA/J. BELL (CORNELL
U.) AND M. WOLFF (SSI), THE HUBBLE HERITAGE TEAM (STSCI/AURA) AND NASA/ESA

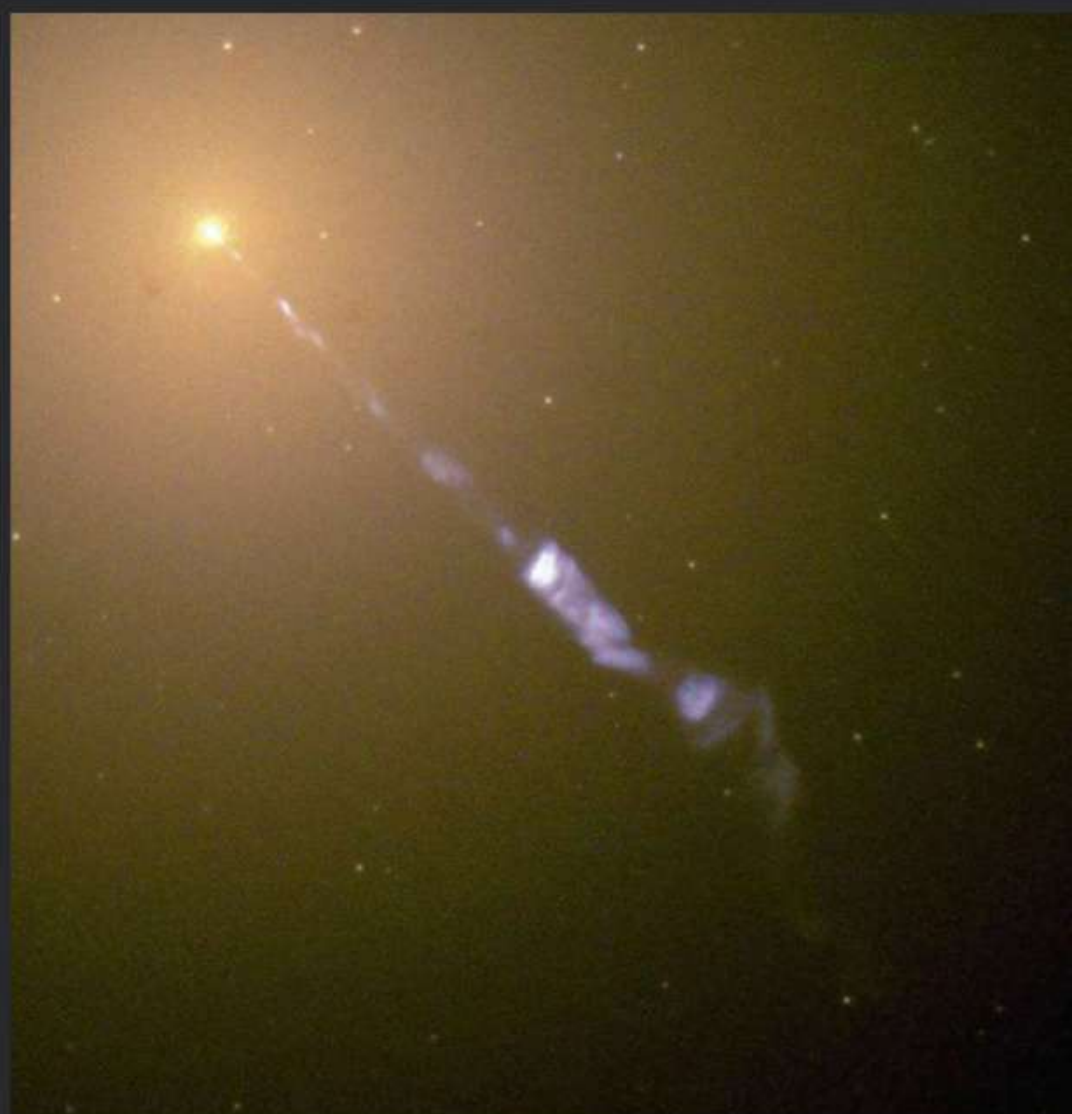




◀ Galactic whirlpool

RELEASED: 21 SEPTEMBER 2015

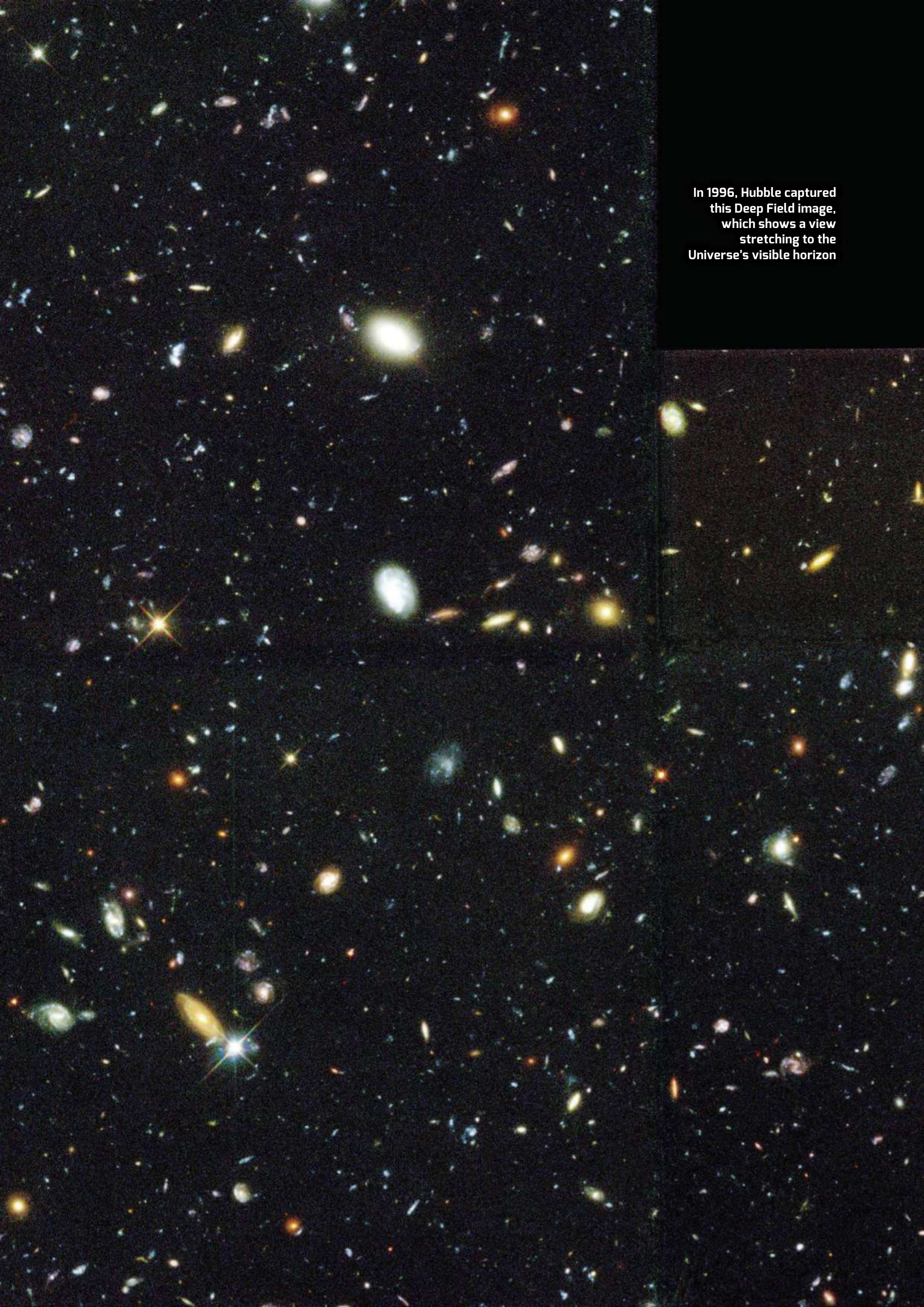
The spiral galaxy M96 looks like a giant whirlpool, swirling in a cosmic sea. Its arms are thought to be asymmetrical because of the gravitational pull of other galaxies within the same group.



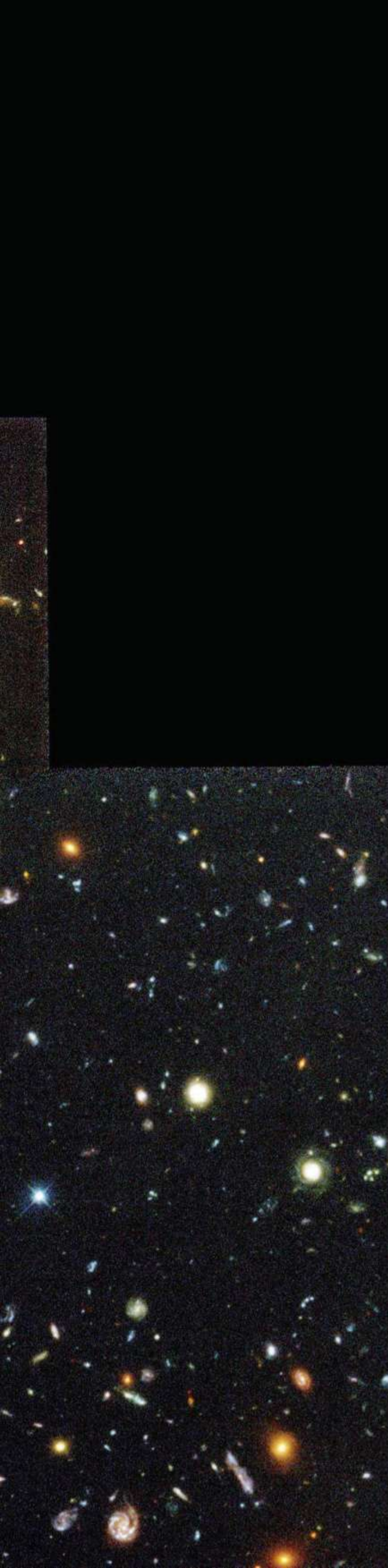
▲ Cosmic torch

RELEASED: 6 JULY 2000

At the centre of galaxy M87 is a monstrous black hole, which powers the jet of electrons and other sub-atomic particles that forms this beam of light slicing through space.



In 1996, Hubble captured
this Deep Field image,
which shows a view
stretching to the
Universe's visible horizon



A view across TIME

Hubble has helped to peer back across the aeons of time and shown that the Universe is growing at an ever faster rate

By Elizabeth Pearson

Hubble's high resolution, large aperture and extreme precision means that it can pull photons out of the darkest reaches of the Universe, looking further back than any visual telescope that came before it. As the light from these distant galaxies and stars has taken billions of years to cross the void, we see them as they were millennia ago, all the way back to the earliest days of the Universe.

"We can compare the nature of the most distant galaxies to those we see closer to us in space and time, to see if they are different. And, in fact, they are," says Jennifer Wiseman, Hubble's senior project scientist. "I think Hubble's most profound contribution has been revealing to us how the Universe has changed over time."

Nowhere is this capability better showcased than in the Hubble Deep

Field images. The first of these was taken in 1995, when the telescope took a 100-hour long exposure – many times longer than normal – of an apparently blank stretch of sky. At the time, some astronomers argued the image was a waste of precious Hubble time, but when the image was put together, they were swiftly proved wrong.

This first image contained almost 3,000 galaxies, some dating back to when the first stars were forming. These appeared to be smaller and more irregular than those in the present day, demonstrating that galaxies do change over time.

Supernovae clues

While Hubble's keen eye has been able to make these out, it has also been key in working out exactly how far away these remote stellar collectives are.

"Hubble observes the Type Ia supernovae that astronomers use to gauge the distance to far away

Top 3 Universe moments

Hubble has fundamentally altered our view on the largest of scales



eXtreme Deep Field

In 2012, the Hubble team released the eXtreme Deep Field. The image covered just 2x2.3 arcminutes, around 1/32,000,000ths of the sky, yet had an exposure time of around 23 days. It looks back through 13.2 billion years of the Universe's history, showing one galaxy as it was when it was just 450 million years old.

Confirming primordial helium

In 1995, Hubble was finally able to confirm the presence of primordial helium. Theory had predicted that after the Big Bang, the cooling Universe formed both helium and hydrogen, but the former had never been seen before.



Gamma ray bursts

GRBs are the most powerful explosions in the known Universe, but their origins are a mystery. In 2019, Hubble found a GRB had come from the dense environment of a very bright galaxy around 5 billion lightyears away – a potential clue to the kind of conditions that might cause the bright flash of a GRB.

– the realisation that the Universe's expansion is actually accelerating."

Astronomers were surprised when two independent teams discovered this acceleration in 1998. Everyone had assumed that after the Big Bang the expansion would either slow to a stop or plateau to a steady rate. If the expansion is accelerating, then the question arises: what's speeding it up?

"We still don't fully understand," says Wiseman. "It's a very hot topic in astrophysics. We call it dark energy and Hubble has really played a key role in its study."

Today, astronomers believe dark energy makes up around 75 per cent of the Universe. A small portion of the rest is made up of luminous matter, such as the gas and dust that glows in clouds or burns in stars. The remaining 24 per cent is dark matter, another mysterious substance which threads through our Universe, extending out between galaxies and stars.

Dark enigma

This dark matter doesn't interact with light the way normal matter does, making it completely invisible to normal telescopes. But it does interact with the visible Universe through gravity, meaning that Hubble is able to bring this 'unseeable' substance into the light.

"Any type of mass will distort spacetime," says Wiseman. "If you have a very large collection of mass, that distortion might actually create a phenomenon significant enough to be observed."

This effect is known as gravitational lensing, where light from a distant galaxy is bent by the gravity of a huge object, such as a cluster of galaxies. However, the process isn't perfect and by the time the light from the distant galaxy reaches Earth it's usually been badly distorted.

"Hubble is being used to observe clusters of galaxies to detect these

galaxies," says Wiseman.

These supernovae always explode with the same brightness, so by measuring their apparent brightness from Earth astronomers can work out how far away they – and the galaxy they occurred in – must be. Calculating these distances is a key part of one of Hubble's main science goals – measuring the rate at which the Universe is expanding.

"Ever since Edwin Hubble took

observations showing galaxies were receding a century ago, we've known that the Universe appears to be expanding, and that space seems to be stretching," says Wiseman. "But measuring the actual rate of that expansion has been challenging because it requires precise distance measurements. Hubble has helped to make these observations with higher and higher precision, leading to one of its most impactful contributions



“This helps us in two really innovative ways that were never conceived when Hubble was first launched...”

arcs of distorted light,” says Wiseman. “This helps us in two really innovative ways that were never conceived when Hubble was first launched. First is that by looking at the gravitational lensing of the galaxy clusters we can tell something about how mass is distributed in these clusters.”

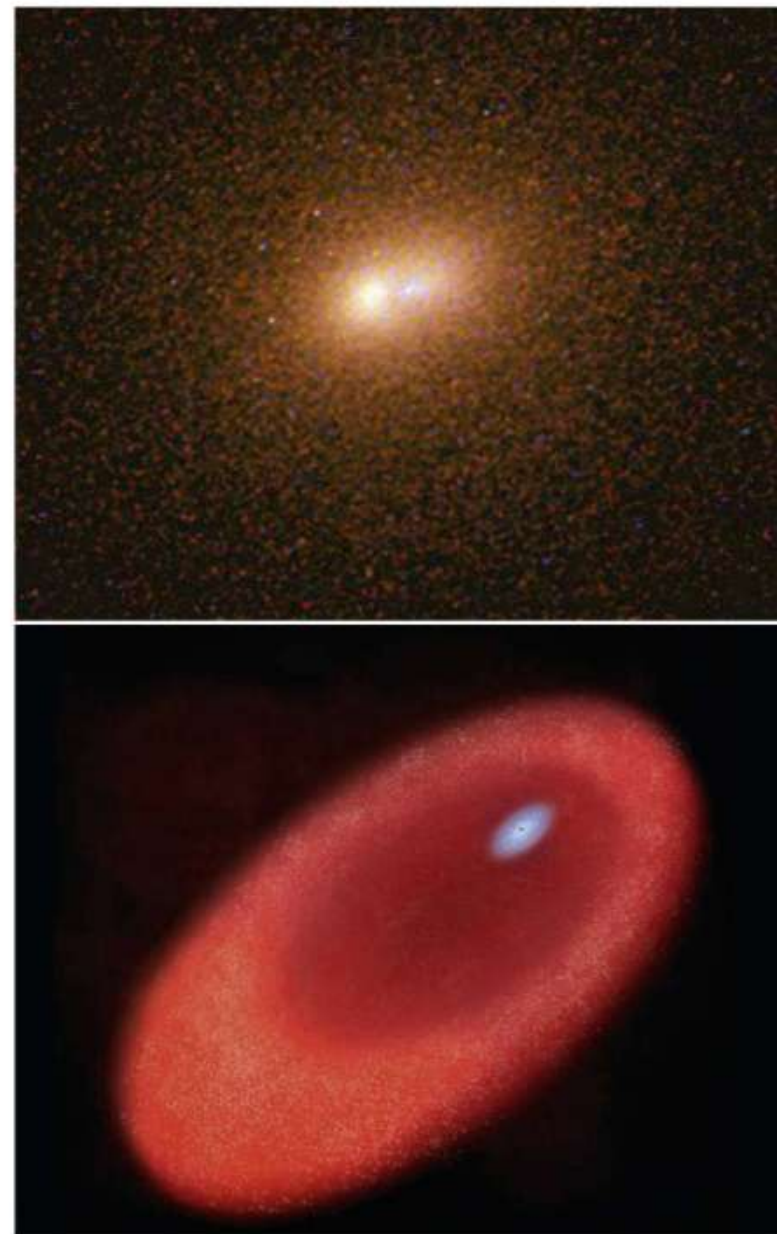
Most of this mass is dark matter. By looking at how much galaxies are distorted, astronomers are able to map out how the mysterious substance is distributed throughout the Universe and through cosmic history.

“Second we can learn more about the background galaxy as it’s being magnified by the lensing effect as well as being distorted,” says Wiseman. “We are seeing galaxies that are more distant and more detailed than we would be able to see without Nature’s

magnifying glass. That’s helping us see the character of galaxies very far back in time and look at how star formation is happening within physical regions in the galaxy.”

Spotting black holes

Another seemingly invisible object that Hubble has helped illuminate are supermassive black holes. These dense bodies are several billion times more massive than our Sun and are thought to lie at the heart of most galaxies. Before Hubble, these black holes were entirely theoretical. The only evidence of their existence were radio observations of distant galaxies known as quasars, which contained objects around the size of the Solar System but which shone brighter than any other known thing in the Universe.



▲ The core of the Andromeda Galaxy (top) and an artist's impression of it (bottom). Both images show a disc of stars (in blue) that were spotted by Hubble in 1995, and used as evidence for a huge black hole

Hubble was able to determine that the radio emissions were coming from the centres of the galaxies that held them, most likely from extremely hot gas that was being intensely heated as it swirled around a giant black hole.

In 1997, the Space Telescope Imaging Spectrograph was installed on Hubble. This instrument was much better at looking at the region close to a galaxy’s centre, and it could make out the rapid movement of stars caught in orbit close to a black hole. The instrument soon found them, definitively proving the existence of supermassive black holes.

For the last 30 years, Hubble has helped astronomers to pull out photons from the deepest depths of space, and even illuminated places in our cosmos where no light shines, helping to reveal the Universe’s darkest secrets.

NASA/ESA/G. ILLINGWORTH/D. MAGEE, AND P. OESCH (UNIVERSITY OF CALIFORNIA/SANTA CRUZ)/R. BOUWENS (LEIDEN UNIVERSITY) AND THE HUDF09 TEAM, MALEKAS85/ISTOCK/GETTY IMAGES, NASA/ESA AND M. KORNMESSER, ESA/HUBBLE/NASA/RIVERA-THORSEN ET AL, NASA/ESA AND T. LAUER (NOAO/AURA/NSF), NASA/ESA AND A. FEILD (STSCI)

Interview

Kevin Hartnett

Hubble's science operations manager joined the team in 1997, and is responsible for overseeing scientific aspects of the space telescope's operations. With a bachelor's degree in physics and astronomy, his career began in private industry before he jumped ship to work at NASA

How is Hubble doing?

It's performing at the peak of its capabilities and functioning marvellously. There aren't as many available backups as there were some years ago. For instance, Hubble has six gyros to keep itself orientated, but only three are active and we need three to do our best science.

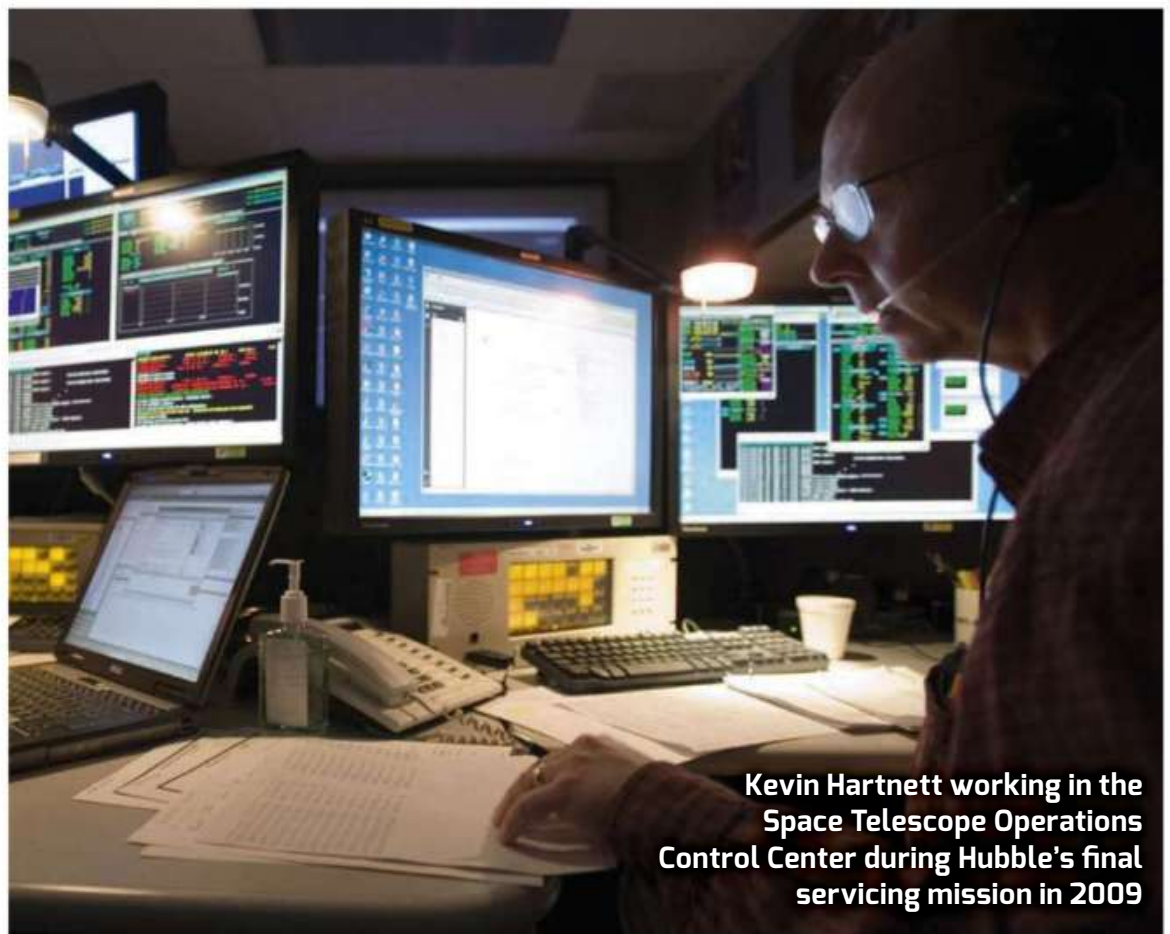
Our engineers are coming up with clever ways to combat aging. Things dim, they fade, one side of the detector has a greater sensitivity than the other. But they've kept the observations really at the forefront of what anyone can do on the ground or in space, and that's pretty remarkable.

What sets Hubble apart?

It's a one-stop shop for very stable, high contrast imaging and spectroscopy from the near infrared wavelengths right through to the ultraviolet, with a 2.4m mirror above the atmosphere. We have very fine guidance sensors too. In layman's terms, it's like being on top of the Washington Monument in Washington, DC and keeping a laser pointer on a dime on the top of the Empire State Building in New York City 330km away for 24 hours. So once we lock on, we really lock on target.

What type of research does Hubble do?

Solar System astronomy, galaxies, large scale structure of the Universe, and everything in between – Hubble has made major contributions to every astronomical field. There are also legacy programmes. For instance, there's a large project right now to observe every Milky Way globular



Kevin Hartnett working in the Space Telescope Operations Control Center during Hubble's final servicing mission in 2009

"We have very fine guidance sensors. It's like being on top of the Washington Monument and keeping a laser pointer on a dime on the top of the Empire State Building in New York City 330km away for 24 hours."

cluster. Not because someone wants to write a paper on all 150 clusters, but the data is there if someone ever does.

Does the old data still get used?

Oh my, yes. There's a lot of interesting science you can do with a 25-year baseline. If you've got good observations from 25 years ago, you can compare them to similar observations today. You can see jets actually moving out of the big quasar in M87 over that period of time. You can

calculate velocities. Scientists can get a lot out of data like that.

How long does Hubble have left?

Hubble doesn't have a propulsion system and it is slowly falling to Earth. A report from September 2018 predicts Hubble re-entry no earlier than 2027, and the mean date is around 2038. We're very in tune with the performance of the telescope and we're trying to pamper all of its systems, to keep it running as long as possible.

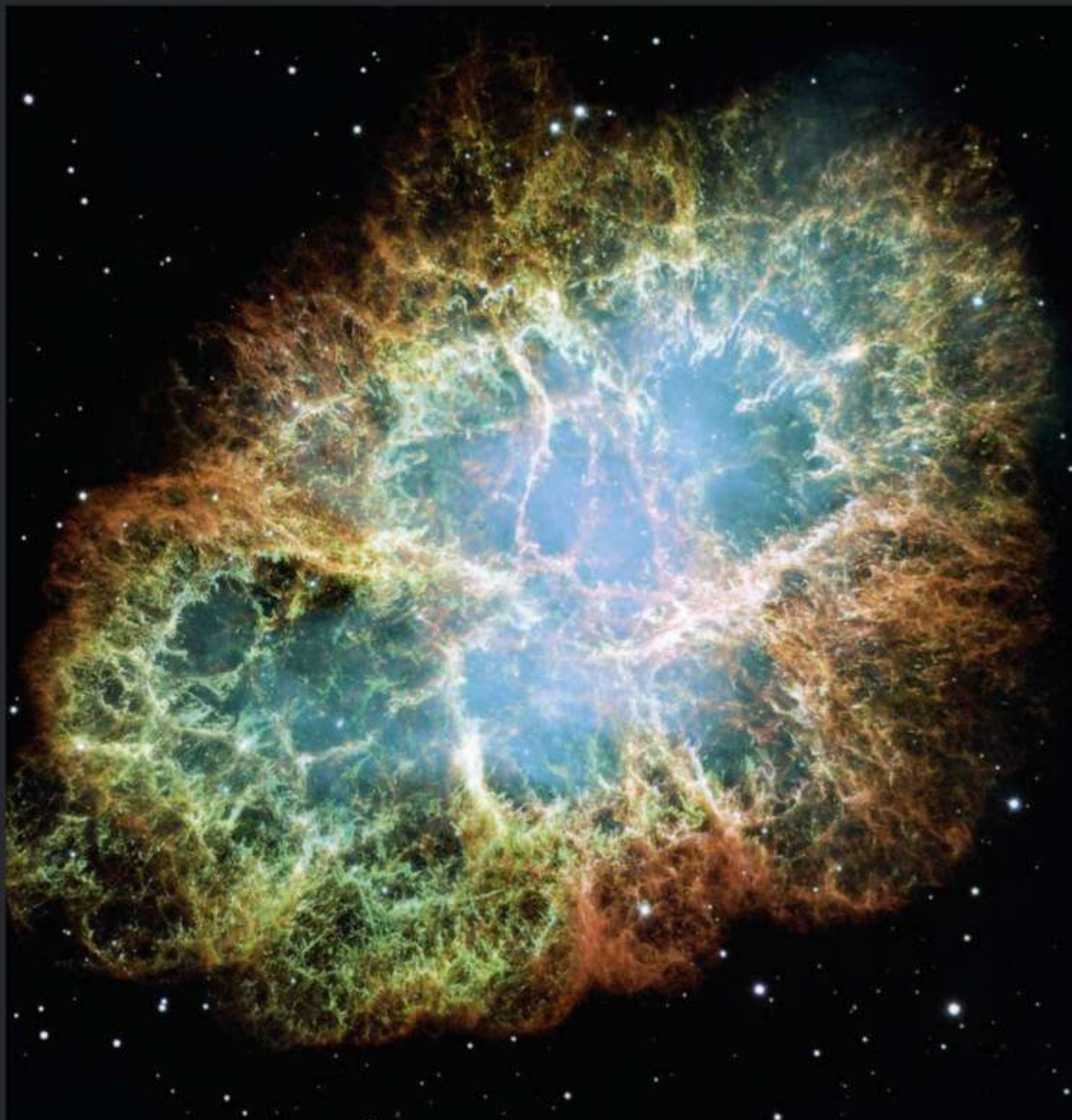




◀ Crab close up

RELEASED: 1
DECEMBER 2005

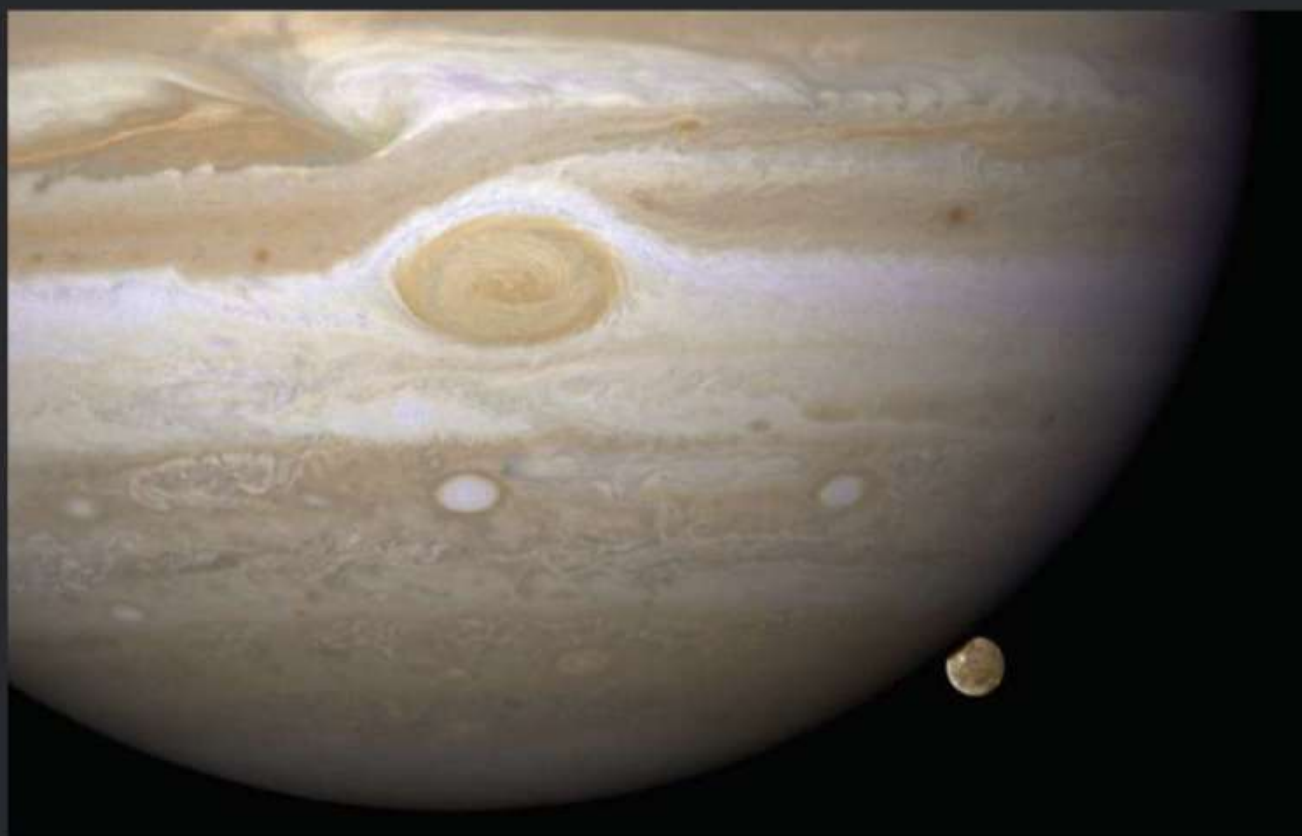
This is the highest resolution image ever made of the entire Crab Nebula, the wreckage of a supernova explosion. At its centre is a rapidly spinning neutron star – the crushed, ultra-dense core of the exploded star. The vibrant blue light is from electrons zipping along magnetic field lines created by the star. The orange spindles around the outside are the rest of its remains and consist mostly of hydrogen.



◀ Deadly dual

RELEASED:
11 NOVEMBER
2013

Galaxies NGC 4038 and NGC 4039 are locked in a deadly dual. Known collectively as the Antennae Galaxies, the pair have spent the past few hundred million years clashing with one another. The violent battle has ripped stars from their host galaxies to form the streaming arc that can be seen between the two.



▲ Peek-a-boo

RELEASED: 18 DECEMBER 2008

One of Jupiter's moons Ganymede is captured just before it ducks behind the gas giant. Ganymede takes seven days to complete an orbit of Jupiter. It's the largest moon in the Solar System – and even larger than the planet Mercury.



▲ Cosmic sculptures

RELEASED: 16 SEPTEMBER 2010

Fierce stellar winds and savage radiation from massive stars sculpt cold molecular clouds, creating impressive pillars in the Carina Nebula.



August 9, 2001



August 10, 2001



August 14, 2001



September 4, 2001

◀ Wild weather

RELEASED: 11 OCTOBER 2001

Over the course of a month, Hubble and the Mars Global Surveyor (MGS) captured this set of images, which shows a huge global dust storm ravaging the Red Planet.

Black hole beast

RELEASED: 23 DECEMBER 2019

At the centre of this galaxy ESO 021-G004 lies a supermassive black hole. Material falling in towards the black hole gets swept into an accretion disc, where it is superheated and emits high-energy radiation, before being devoured by the voracious singularity at the centre.

NASA/ESA/E. SABBI (STSCI), J. BELL (CORNELL UNIVERSITY), NASA/ESA AND THE HUBBLE HERITAGE TEAM (STSCI/AURA), NASA/ESA/J. BELL (CORNELL U.) AND M. WOLFF (SSI)

Hubble's final act will be to safely
burn up in Earth's atmosphere,
probably some time in the 2030s



STOCKTREK IMAGES, INC./ALAMY STOCK PHOTO

HUBBLE
SPACE TELESCOPE

30 THE
LEGACY

Hubble is destined to end its physical life in the fireball of a controlled atmospheric re-entry. Yet the space telescope's legacy will live on: science will continue to be done with its remarkable observations, and its presence in the hearts and minds not just of space experts but also wider society is assured. This section looks at the cultural impact of Hubble's imagery and how we view our place in the Universe, and reveals the space observatory that will replace it – the James Webb Space Telescope.



Winning hearts and minds

Despite early hitches and costly repair missions, Hubble has been a huge success story – taking incredible images that have captured the attention of people all around the globe

ESA/HUBBLE

By Ben Evans



▲ Hubble reached 1 million Facebook likes in 2014. Hubble staff took selfies or group photos to show Facebook friends the people working behind the scenes. Members of the public responded with “I’m a Hubble friend! I’m one in a million”

Ed Weiler, program scientist for Hubble, once remarked: “The most important thing Hubble has done is answer questions we didn’t know how to ask in 1990, Hubble keeps telling us that our textbooks aren’t being followed by the actual Universe.” When the STS-31 astronauts put the telescope into orbit, they joked that they ought to burn their college astronomy books when they got home, for soon everything humanity thought it knew would vanish into obsolescence.

They were right. Hubble has overturned our perception of the cosmos and our infinitesimally small place within it. The effect for the person on the street has been pervasive and profound.

Leading that queue of people are the astronauts themselves. For spacewalker Mike Massimino, Hubble sits alongside Egypt’s pyramids and the Great Wall of China as one of our grandest engineering accomplishments.

It prods a primal instinct to explore and seek out the unknown for its own sake. Until the telescope arrived,

said three-time Hubble visitor John Grunsfeld, the public had little concept of what the Universe was really like: “Astronomy is an ancient science and people want to know the answers to some fundamental questions. Hubble has been a tool that has made accessible to the public answers to those questions, not only with scientific answers – numbers like 13.7 billion years for the age of the Universe – but also unbelievable pictures of what the Universe looks like.”

And while this ancient science might not reap economic benefits, said Mike

Hubble in the media

From films and literature to music and fashion, modern culture is indebted to Hubble's imagery

Before Bruce Willis strutted his stuff and started blowing up asteroids in the movie *Armageddon*, the immortal line "We're movin' the Hubble" underscored the importance that even Hollywood placed in NASA's premier observatory. Admittedly, like so many silver-screen representations of space technology, 'moving' the telescope carried a touch of artistic licence, but the sentiment was there.

Hubble has extended its reach not only deep into the Universe, but also deep into hearts and minds over the last three decades. As Shuttle veteran Kathy Sullivan noted in her memoir, *Handprints on Hubble*, it garners many millions of hits when typed into any internet search engine, and its imagery has become firmly embedded in our popular consciousness, manifesting itself on calendars and mouse-pads, screen-savers and tote bags, tattoos and socks.



▲ Highlights of entries to the Hubble Pop Culture competition

In recognition of its 20th anniversary in 2010, a Hubble Pop Culture competition awarded prizes for artistically impactful representations of the telescope. Headlined by Pearl Jam's Binaural album, whose image of the Hourglass Nebula captured 13 lightyears of celestial distance in the span of a CD cover, other winners included a Hubble-skinned guitar, prints of the telescope's images on blouses, gowns and shirts at New York Fashion Week and even cross-stitch patterns and bubblegum.

➤ Foale, who replaced Hubble's computer in 1999, astronomy is an academic specialty whose knowledge filters directly back into society: "You only have to be a father and son, or father and daughter, going out and looking at the stars, and you get what it's about. It's captivated people for many thousands of years."

Key questions

Most of the men and women who flew to Hubble were not astronomers or astrophysicists; they included military test pilots, engineers, seismologists, oceanographers, physicians and even a veterinarian. But all appreciated the philosophical sea-change that Hubble's arrival on the scientific scene represented. "In the deep of ourselves, everybody, consciously or unconsciously, is always asking: Why are we here? What is our past? Where are we going?" said robot arm operator Jean-Francois Clervoy. "Astronomy is one of the scientific fields that answers some of those questions."

And for Curt Brown, who commanded the third servicing



▲ Vet Rick Linnehan (left) operated on Hubble during mission STS-109 in 2002

mission, the excitement boiled down to a singular question: How far does that go? "It could be going out to a certain place and stopping," he mused. "If it stops, what's on the other side? If it doesn't stop – if it goes on forever – tell me what 'forever' is all about."

"Most of us are driving around town,

commuting to work, and we rarely look higher than the next exit sign on the freeway," said spacewalker Drew Feustel. "Hubble allows us to look so much farther beyond that, into the stuff our dreams are made of."

Time machine

Veterinarian Rick Linnehan operated on his biggest ever beast when he did open-heart surgery on Hubble in 2002. As a child, he adored *Star Trek*, fascinated by its improbable-looking planets and psychedelic galaxies – only to discover that the real-life Universe is far stranger and more exotic than any fictional construct.

"I consider Hubble to be part of the American myth," said Linnehan. "When you gauge history and time, scientific knowledge and how it progresses, and society and civilisation, you've got Hubble in there as a big bookmark." Its capacity to see deeper into the Universe transformed it, in the words of spacewalker Steve Smith, into humanity's own time machine.

"Hubble has this allure to it," said Smith. "So any time you're on a Hubble

"I would put Hubble's total social impact close to Apollo 11"

Hubble's scientific and societal impact on the world below has been huge

flight, it really is a magical experience."

For Grunsfeld, it was his life's most meaningful work. "People have to decide for themselves what kind of things they want to do and what's worth risking," he said. "For me, working on Hubble is worth risking my life for." Others saw equivalent value, but for different reasons. Foale wanted to reach its immense altitude. "I want to see the Earth, high," he said. "I've always wanted to be on a Hubble flight, because it goes about as high as a Shuttle can go."

Personal impact

Like many of us Earth-dwellers, astronauts trace significant life events alongside the telescope. Greg Johnson, who piloted the last servicing mission, was hired by NASA the day before Hubble's launch, while robot arm operator Megan McArthur was an undergraduate contemplating a space career. And fellow robotic specialist Nancy Currie still derives joy and pride

The full beauty of the Cat's Eye Nebula is evident from an image captured by Hubble in 2008



in taking her family outside at night, pointing at the star-like Hubble tracking across the dark sky and knowing that she helped put it there.

Picking a 'favourite' image from the telescope is an exercise in frustration. Johnson and McArthur chose the Cat's Eye Nebula, with its blend of explosive reds, blues, purples and greens, while Grunsfeld and Feustel admired the clown-like face of the Eskimo Nebula, which represents the lingering death

of a star not unlike our Sun. Spacewalker Mike Good loved the Hubble Ultra Deep Field of 10,000 galaxies, dating back to the dawn of time. "Not the most beautiful, but there's so much captured in that image."

Hubble's far-reaching significance – measuring the age of the Universe, looking back within a few hundred million years after the Big Bang, finding thousands of galaxies in seemingly empty patches of sky and demonstrating that black holes are not only real, but commonplace – makes it

hard to imagine how future telescopes can match its immense cultural impact.

"I can't think of anything in between bootprints on the Moon and Hubble that have had that kind of reach," said Kathy Sullivan, a veteran of three Shuttle missions. "And not just a reach in terms of headcount and numbers, likes and downloads, but in imagination and inspiration in my lifetime. I would put Hubble's total social impact awfully close to Apollo 11."

Interview

Ray Villard

Specialising in the public communication of astronomy since 1974, Ray Villard is the news director of the Space Telescope Science Institute in Baltimore, Maryland. An author, journalist, scriptwriter, editor and Primetime Emmy Award nominee, he turns Hubble's scientific discoveries into gripping stories

“You’d have to be living in a cave if you didn’t see Hubble pictures,” says Ray Villard, Hubble news chief at the Space Telescope Science

Institute (STScI). “The beauty of Hubble, and astronomy in general, is it knows no political boundaries; it knows no international boundaries. Over here, Republicans *and* Democrats love us. We get a lot of traffic from Japan and China, a lot of our stories are on Al Jazeera and if you don’t have the internet there are many publications that print our pictures and stories.”

Hubble was just one of four great observatories launched by NASA between 1990 and 2003. But its edge is that it was first. “It became equated with astronomy and the pictures were hard to compete with,” says Villard. “We were first out of the gate. We captured the Universe in images that the public could understand and relate to.” Seizing market-share in this fashion allowed Hubble’s pictures to communicate with a broader demographic. “They transcend trying to understand scientific ideas,” he explains. “They appeal at a visceral and emotional level. They say something about the mystery and wonder of the Universe. They go beyond a normal scientific dialogue.”

This appeal was aided by the parallel rise of the internet. “This was the democratisation of astronomy,” Villard adds. “Anybody, anywhere, could download these pictures and before Hubble was launched, it was harder.

Ray and his team celebrate Hubble’s 1,000th press release



“It’s the old storyline where there is expectation, then there’s fall from grace, then there’s melodrama, but then there’s redemption.”

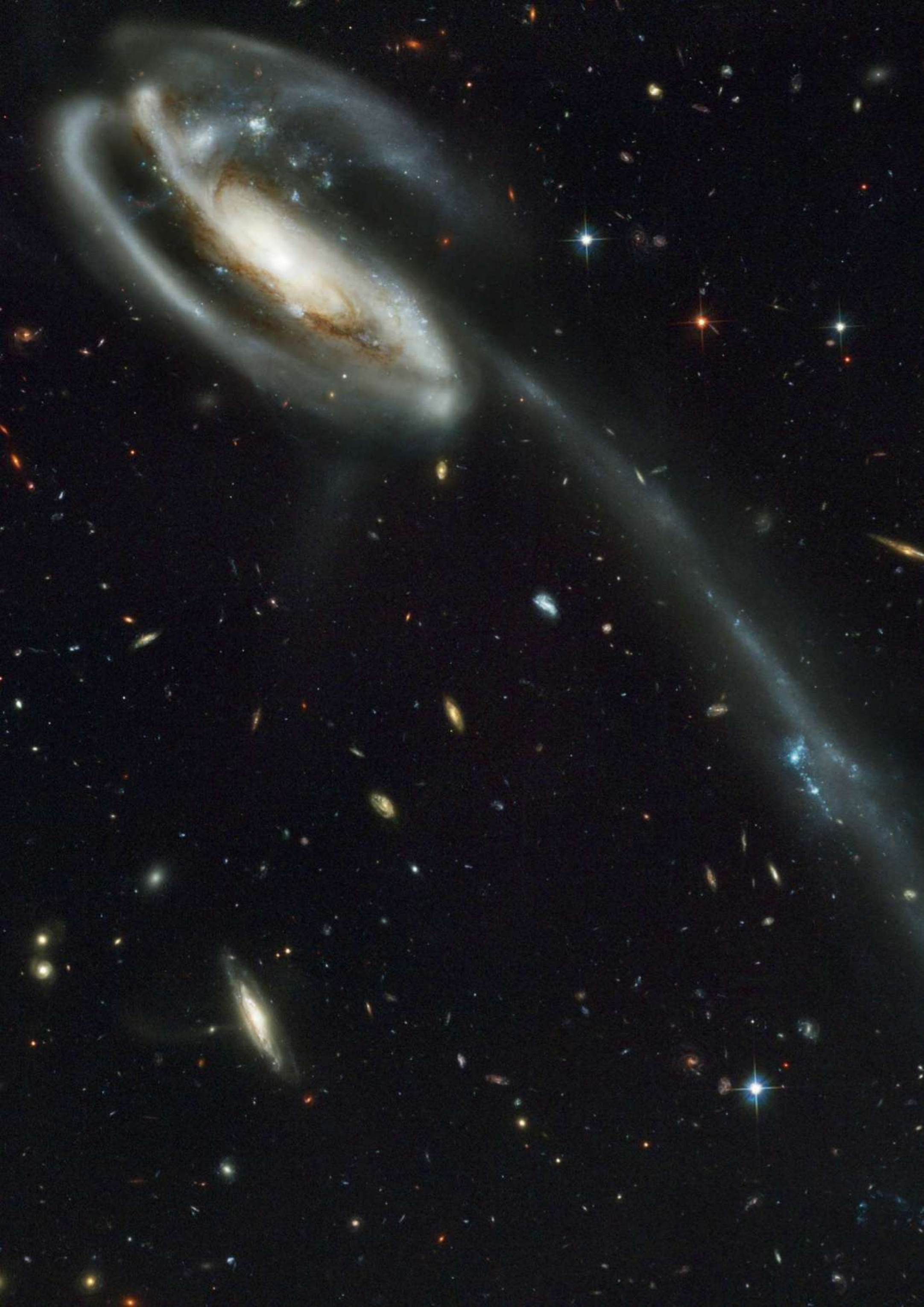
There really weren’t that many, or you’d have to mail off to the observatory, and frankly most pictures were black-and-white. Whatever colour ones that were done were usually false-colour and pretty garish. With Hubble, we combined artistry and scientific integrity with crafting pictures that were both informative and aesthetic. It set a new benchmark for how other observatories should do this.”

Like all good Hollywood epics, Hubble possesses an Indiana Jones story-arc of its own, Villard suggests. “You could make a movie about it. And it’s the old storyline where there is expectation, then there’s fall from grace, then there’s melodrama, but

then there’s redemption,” he explains. “And people love those kinds of stories.” Villard thinks that although the mid-1990s were Hubble’s heyday of wowing the public, its level of interest has never waned. That interest became critical when the final Hubble servicing mission was cancelled. “There was uproar among the public, who wanted that mission reinstated,” he says. “Kids collected lunch money to send to NASA. There has never been an instrument in the history of science so embraced by the public.”

And if Hubble were turned off tomorrow? “All hell would break loose,” chuckles Villard. “People would go nuts. This is a people telescope.”





◀ The tadpole

CAPTURED: 1 & 9 APRIL 2002

The spiral galaxy UGC 10214 looks a bit like a tadpole with its long tail of stars. The tail is the remains of a 'hit-and-run' accident with a smaller galaxy (the blue dot in the upper left corner of the more massive galaxy) that strayed too close.



▲ Northern lights

RELEASED: 30 AUGUST 2018

Saturn and its northern aurorae, which differ to those on Earth as they are mainly visible in the ultraviolet – a part of the electromagnetic spectrum blocked by Earth's atmosphere.



◀ Red giant

RELEASED: 12 AUGUST 2019

This is planetary nebula NGC 2022. When a star like our Sun grows old, it glows red – earning the name 'red giant' – and sheds its outer layers, which form a shell of surrounding gas that glows from the UV light emitted by the star's shrinking core.

NASA/HOLLAND FORD (JHU) THE ACS SCIENCE TEAM AND ESA, ESA/HUBBLE/
NASA/A. SIMON (GSFC) AND THE OPAL TEAM/J. DEPASQUALE (STSCI) L. LAMY
(OBSERVATOIRE DE PARIS), ESA/HUBBLE & NASA/R. WADE



▲ Anaemic spiral

RELEASED: 5 FEBRUARY 2009

The spiral galaxy NGC 4921 has been dubbed anaemic because of its ghostly colour – a result of its low rate of star formation and low surface brightness.

◀ Zoom in

RELEASED: 19 JANUARY 2015

This close-up image of NGC 4217 is perfect for studying dust structures, as the spiral galaxy provides an edge-on view from Earth. Analysing the brown wisps of dust can help astronomers identify exactly how gas and dust is ejected from spiral galaxies.



Looks can be deceiving

RELEASED: 16 DECEMBER 2004

The Helix Nebula may look like a simple doughnut shape when viewed from Earth, but new evidence suggests that it is actually made up of two gaseous discs nearly perpendicular to each other. The orangey red ring is the gas emitted by the central star as it sheds its outer layers.





The JWST's huge primary mirror dwarfs a technician during a pre-test in 2016

Looking back, looking forward

Sometime in the next couple of decades Hubble will cease to exist. But a new space telescope is set to launch – the JWST

By Ben Evans

Between parents and children, there will always be similarities, as the outward looks, charisma and charm of one generation passes inexorably to the next. But for Hubble and its successor – the James Webb Space Telescope, presently set to launch aboard an Ariane 5 rocket from Kourou, French Guiana, in March 2021 – there is little in the way of physical likeness between these two astronomical titans of the past, present and future. Admittedly, Webb promises to follow studiously in Hubble's footsteps, peering back to the very dawn of time, a few hundred million years after the Big Bang, observing the earliest galaxies and examining exotic objects far beyond our Solar System. Other than that, Webb could not look more dissimilar to Hubble if it tried.

From the perspective of winning public hearts and minds, it seems

unlikely that we will see another instrument with the singular appeal of Hubble in our lifetimes. "I think it's going to be a watermark for quite some time," said Shuttle veteran Kathy Sullivan. "My sense is that's true scientifically and true from a cultural point of view."

Twenty-five years in the making, Webb is a joint endeavour between NASA, the European Space Agency and the Canadian Space Agency. It will operate further from Earth than Hubble does, with a much bigger mirror and far greater sensitivity in the critical infrared portion of the electromagnetic spectrum. Yet the two telescopes share a handful of unenviable common links: both swelled grotesquely beyond their allotted budgets, both came within a whisker of cancellation, both suffered withering criticism from scientists and politicians alike and both succumbed to extensive delays.

Named after former NASA Administrator James Webb (1906-1992), under whose watch Project Apollo to



Preparing Hubble's funeral

The space telescope has been readied for its eventual departure from orbital space



The circular soft capture mechanism that will one day be used to dock a robotic vehicle with Hubble to take it out of action

With no propulsion system of its own, the school-bus-sized Hubble carries the potential to shower a city with flaming debris if its final descent into oblivion is an uncontrolled one. Early plans to bring it back to Earth aboard the Shuttle for permanent display in the Smithsonian, sadly, came to nothing following the 2003 Columbia disaster, and it seems increasingly likely that a robotic spacecraft will instead guide Hubble harmlessly into a Pacific grave.

During the final shuttle servicing mission in 2009, a soft capture mechanism was added to allow this future robotic vehicle – whose identity remains undefined – to dock with the telescope and execute a final kamikaze dive into our atmosphere.

As for when that will be, there are few certainties. “A lot will depend on what’s working and what isn’t,” said Neill Reid, Hubble’s associate director of science, noting that its WFC 3 and COS instruments have greater electronic redundancy and may survive longer than their older STIS and ACS siblings. “As to when the decision gets made, that’ll be based on monitoring Hubble’s orbital behaviour. It will be more difficult for NASA to attach the de-orbit vehicle if Hubble is tumbling in orbit, so spacecraft stability will be a factor.”

➤ land men on the Moon finally bore fruit, Hubble’s successor came into being in 1996, saddled with the rather drab moniker of ‘Next Generation Space Telescope’. Six years later, it was renamed in Webb’s honour, not just because of what he did for Apollo, but in recognition of the administrator’s work to fund dozens of space science missions. From the outset, the mechanical Webb’s distinctive – and almost monstrous – appearance set it at odds with the tube-shaped instruments that most of us associate with the word ‘telescope’. Its optical element has 18 hexagonal segments of gold-plated beryllium, unfolded in space to produce a mirror 6.5m across, nearly three times larger than Hubble’s.

And whereas Hubble observes in the ultraviolet, visible and near-infrared portions of the electromagnetic spectrum, Webb will focus on lower frequencies from long-wavelength visible light at 0.6 micrometres to mid-infrared at 28.5 micrometres. The most distant objects in the known Universe are heavily ‘redshifted’ – their visible emissions pushed from the ultraviolet end of the spectrum to the infrared end – but for ground-based instruments the

opacity of Earth’s atmosphere makes it hard to comprehensively examine this region. Even Hubble’s keen eyes are at an acute disadvantage here, for the telescope itself radiates in the infrared and its sensors are not cold enough for effective observations.

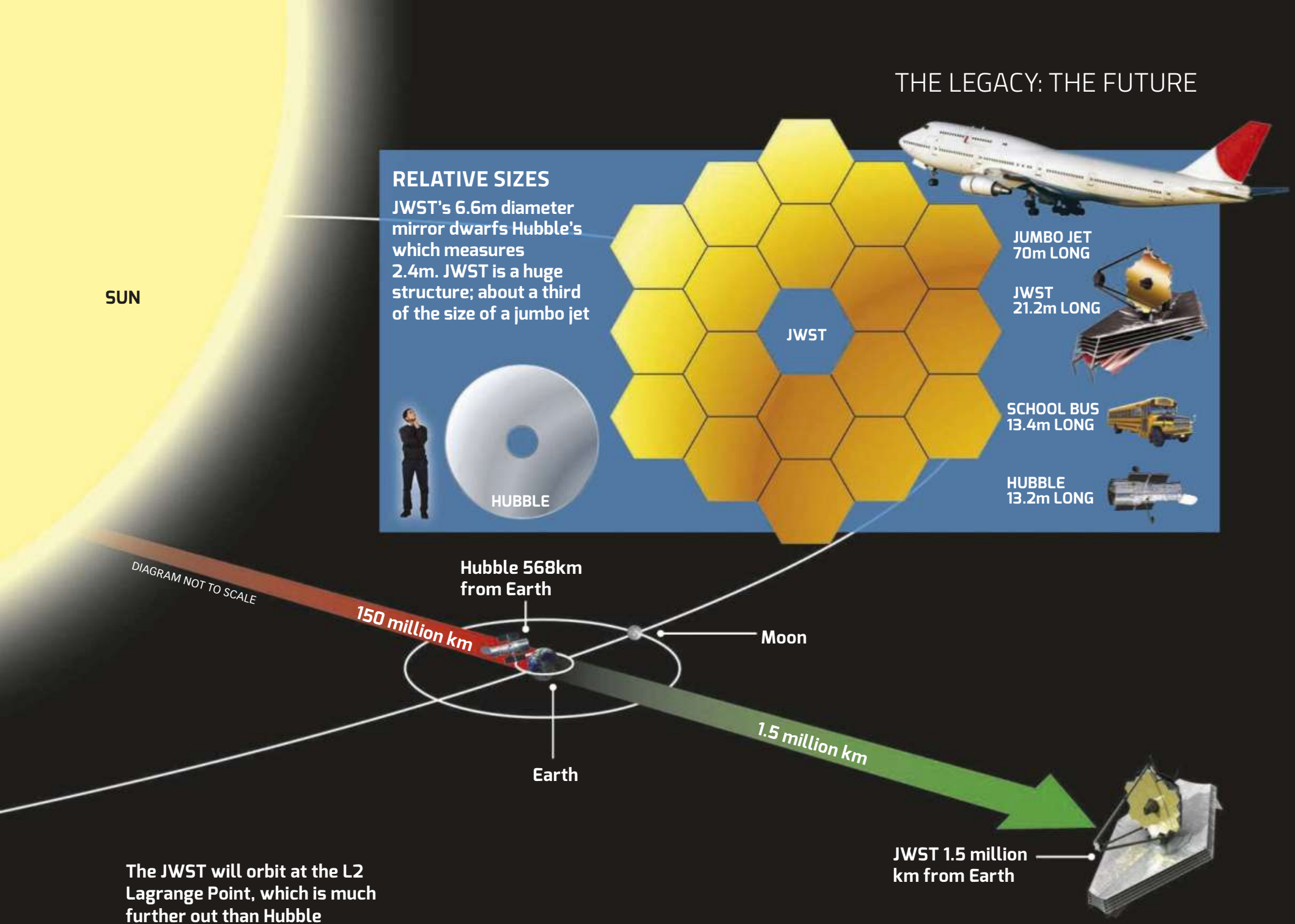
Seeing further

Webb’s infrared sensitivity enables it to view objects far more ancient and significantly more distant than Hubble can see; older even than GN-z11, the highly redshifted galaxy in the constellation of Ursa Major, discovered in 2016 and currently the furthest-known object in the observable Universe. The new telescope’s instruments will peer through colossal clouds of gas and dust, resolve stellar nurseries where new stars are in the process of being born, examine circumstellar disks where young planets are beginning to form, and look deep into the cores of active galaxies to discern black holes lurking within. Webb will observe mysterious brown dwarfs, planets in our Solar System and the atmospheric signatures of exotic exoplanets in the distant cosmos.

With a mirror reminiscent of

the 1980’s British TV game show *Blockbusters*, four infrared sensors and a large, five-layered sunshield made from Kapton and coated with silicon and aluminium, Webb will be placed into a ‘halo’ orbit around the L2 Lagrange Point, some 1.5 million km beyond Earth, where the gravitational influences of our home planet and the Sun meet in balance. Operating from an altitude nearly 3,000 times higher than Hubble for at least five years – and possibly 10, depending on its efficient use of station-keeping propellant – this unique spot will enable Webb to employ its sunshield to blot out unwanted heat and light from the Sun, Earth and Moon, keeping its operating temperatures below -220°C.

But just like Hubble, Webb has fought its own technological and fiscal demons over the years. Initially anticipated to cost \$1.6 billion and targeted to fly as early as 2007, it had already swollen to almost four times that amount by the time construction got underway. Poor management, schedule difficulties and escalating costs forced a major independent review and in 2011 Webb came close to cancellation. By this stage, billions



of dollars had already been spent and three-quarters of its hardware was in production. Disparagingly branded "the telescope that ate astronomy" by the journal *Nature*, it was directly blamed for gobbling funds for other scientific missions. Two years after leaky valves and torn sunshield layers forced the most recent delay, Webb's cost now hovers around \$10 billion.

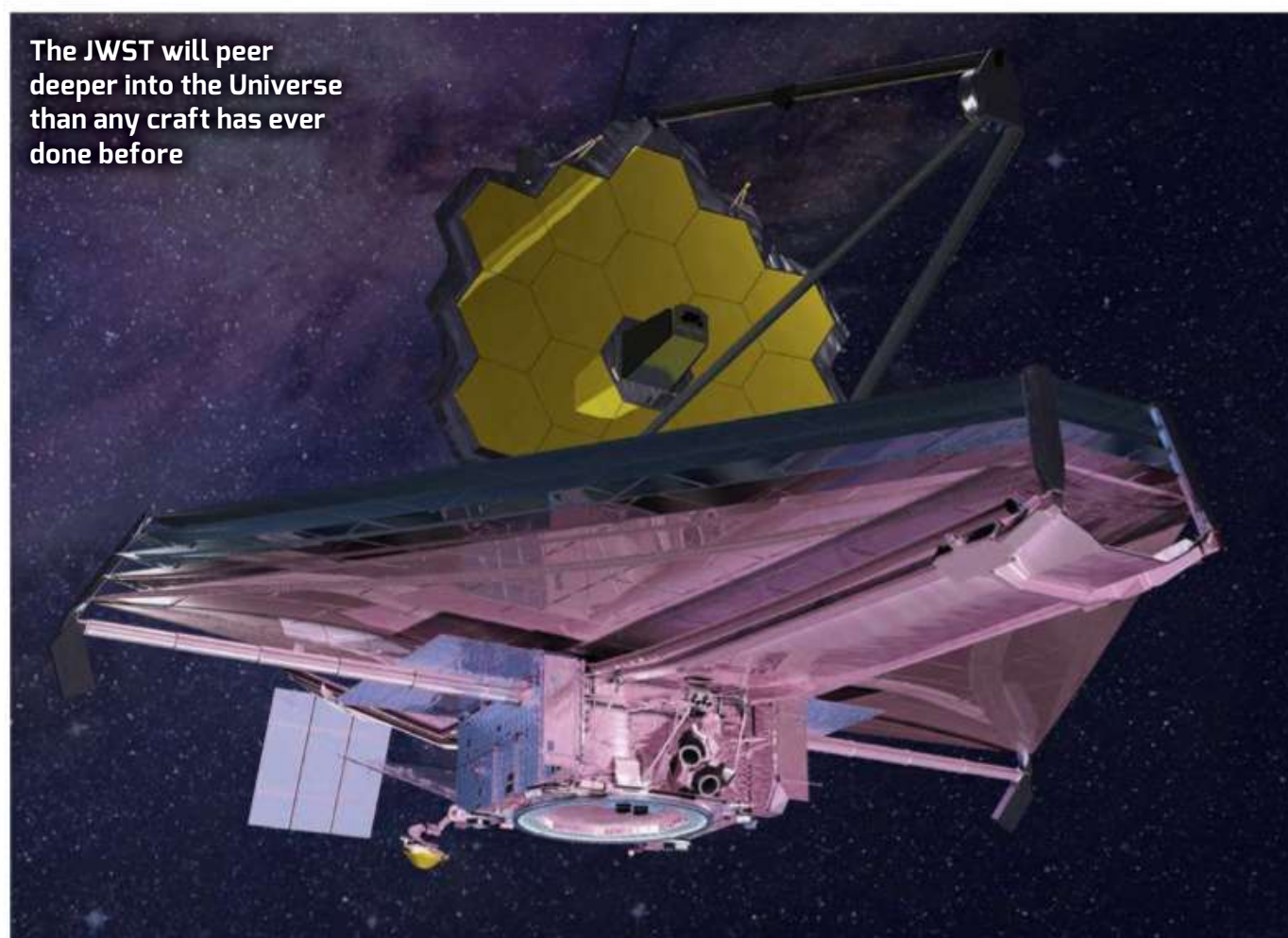
Worth the wait

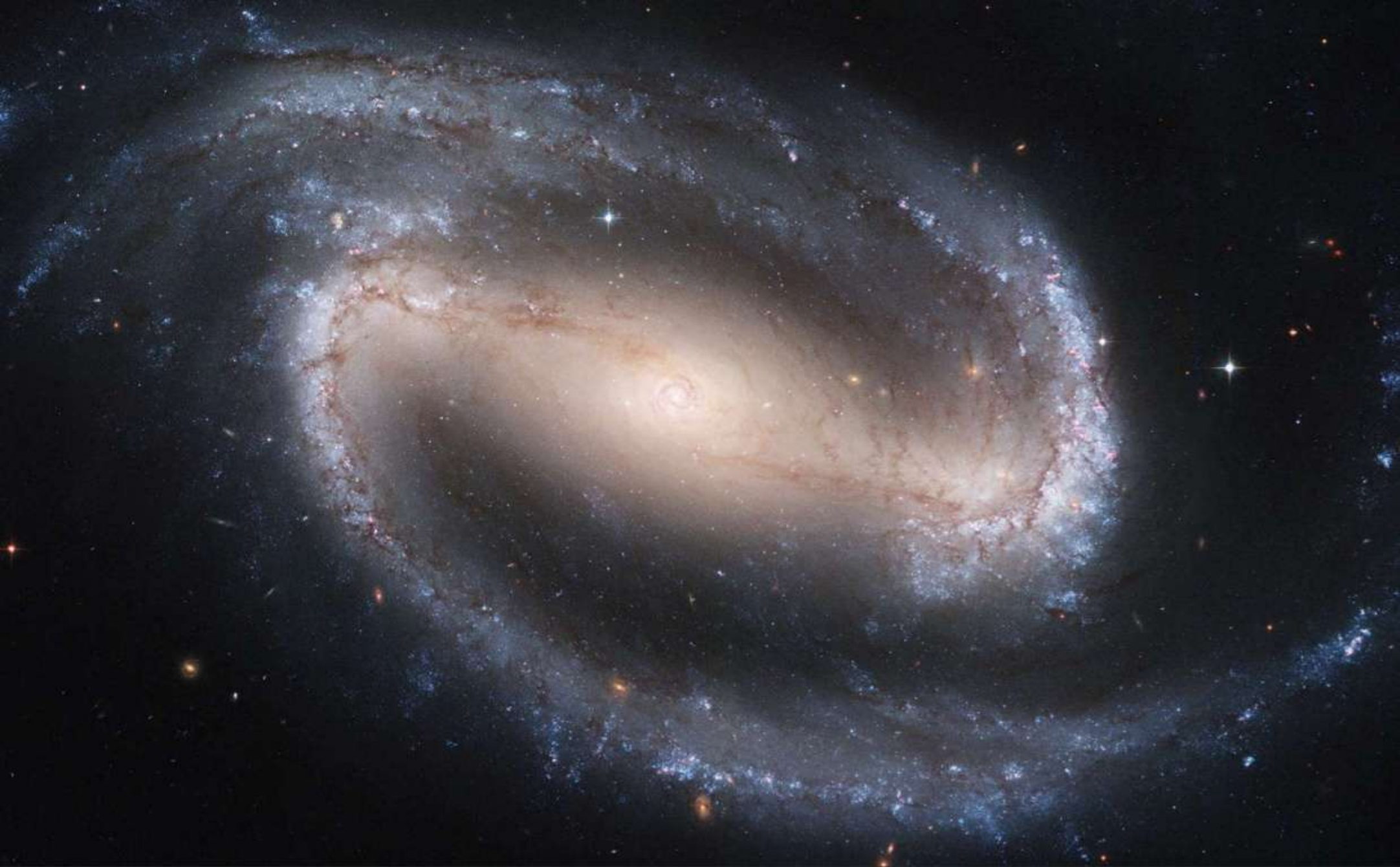
But it promises to be well worth the wait; and hopefully worth its own weight in gold-coated beryllium, too. "Webb will reach deeper into the high-redshift Universe, both because it's more sensitive at infrared wavelengths than Hubble and because the really high-redshift galaxies are redshifted out of Hubble's wavelength range," said Neill Reid, Hubble's associate director of science. "Webb will also probe star formation in the nearby Universe, complementing Hubble because it will be able to see through dust and gas into the central regions of stellar nurseries that are hidden to Hubble. It will revolutionise our

understanding of exoplanets, because it can detect atmospheric atomic and molecular species during transits that can't be seen by Hubble at optical wavelengths."

All told, Reid thinks that Webb may attain a similar level of popular appeal to Hubble itself. But Kathy Sullivan is less sure. "I think Webb's got big boots to fill."

The JWST will peer deeper into the Universe than any craft has ever done before





▲ Barred spiral

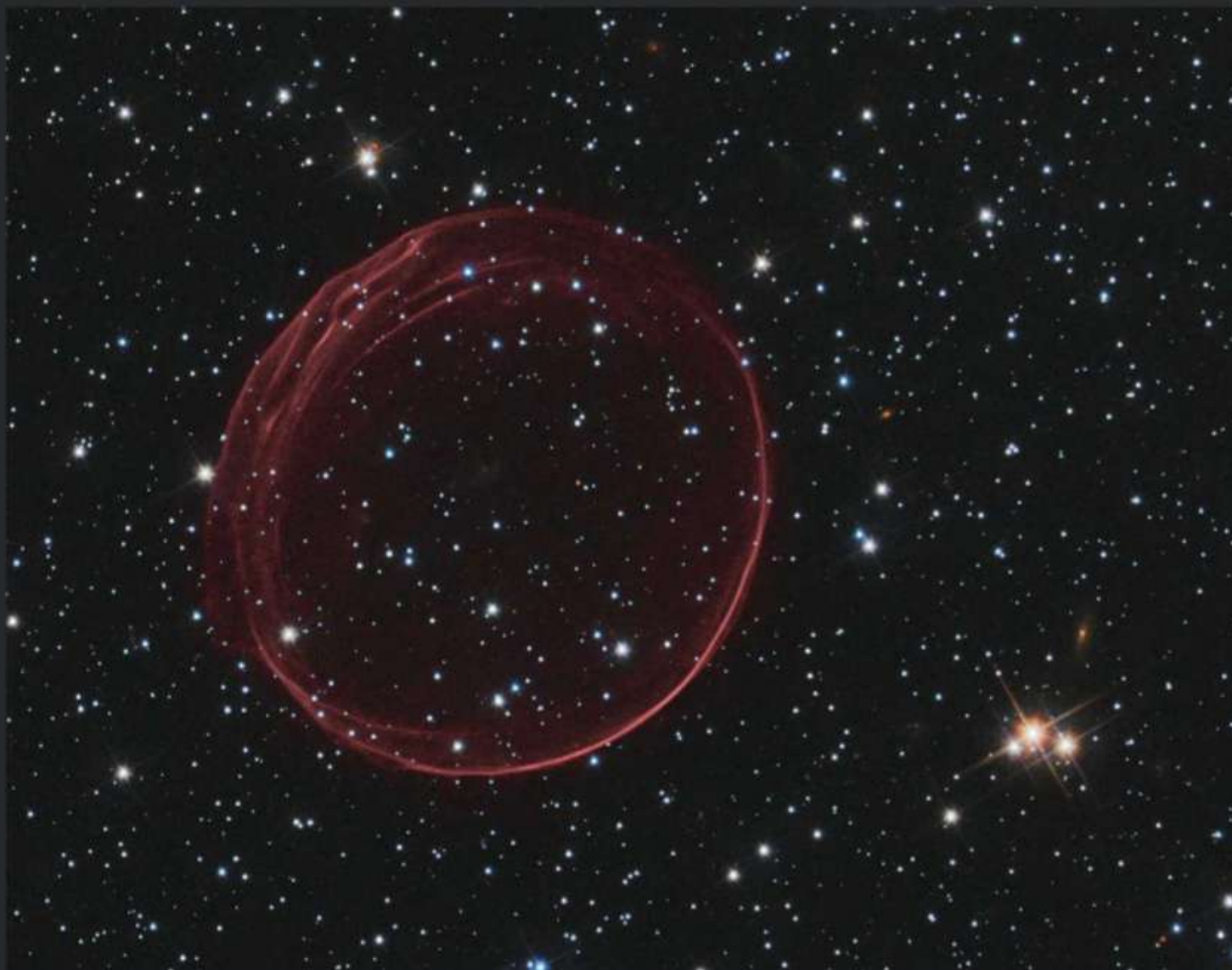
RELEASED: 11 JANUARY 2005

This is the barred spiral galaxy NGC 1300. Barred spirals differ from the usual spiral galaxies as the arms attach to the two ends of a straight bar, rather than winding into the centre.

Celestial bubble ►

RELEASED: 14
DECEMBER 2010

The fragile appearance of this red bubble belies the violent supernova explosion from which it formed. The ripples on its surface may have been caused by variations in the density of the surrounding gas or by fragments from the initial explosion.



NASA/ESA AND THE HUBBLE HERITAGE TEAM (STSCI/AURA) X 3

Ethereal beauty

RELEASED: 17 MARCH 2014

This stunning image is of NGC 2174 – nicknamed the Monkey Head Nebula. Young stars lie encased in gas and dust of rich reds and pinks. The image was released to celebrate 24 years of the space telescope in orbit.



▲ Nude Saturn

RELEASED: 21 OCTOBER 1998

This is what Saturn really looks like. The image shows the planet's true pastel colours – as opposed to the usual false colours that are added. The planet is made of ammonia ice and methane gas, while the rings are mostly water ice. In this image, the tiny dark spot on Saturn is the shadow from its moon Enceladus.



◀ A little gem

RELEASED: 3 AUGUST 2015

NGC 6818 is a planetary nebula whose star has shed its outer layers. Glowing like a jewel, the cloud of gas and dust is only just over half a lightyear across – a tiny gem when compared to cosmic scales. Hence, its nickname of Little Gem Nebula.

HUBBLE HERITAGE TEAM (AURA/STSCI/NASA/ESA), EUROPEAN SPACE AGENCY & NASA, ESA/HUBBLE & NASA

Pinwheel galaxy

RELEASED: 28 FEBRUARY 2006

This grand design spiral galaxy – M101 – has a huge star-forming region at its centre, estimated to contain at least one trillion stars. The whole galaxy is 170,000 lightyears across – nearly twice the diameter of the Milky Way.



Interview

Dr. Eric Smith

The program scientist for the James Webb Space Telescope (JWST), Eric Smith joined NASA Headquarters in 2001. An infrared astronomer by training, he is also one of the Astrophysics Division leads for advance planning and new mission concept development

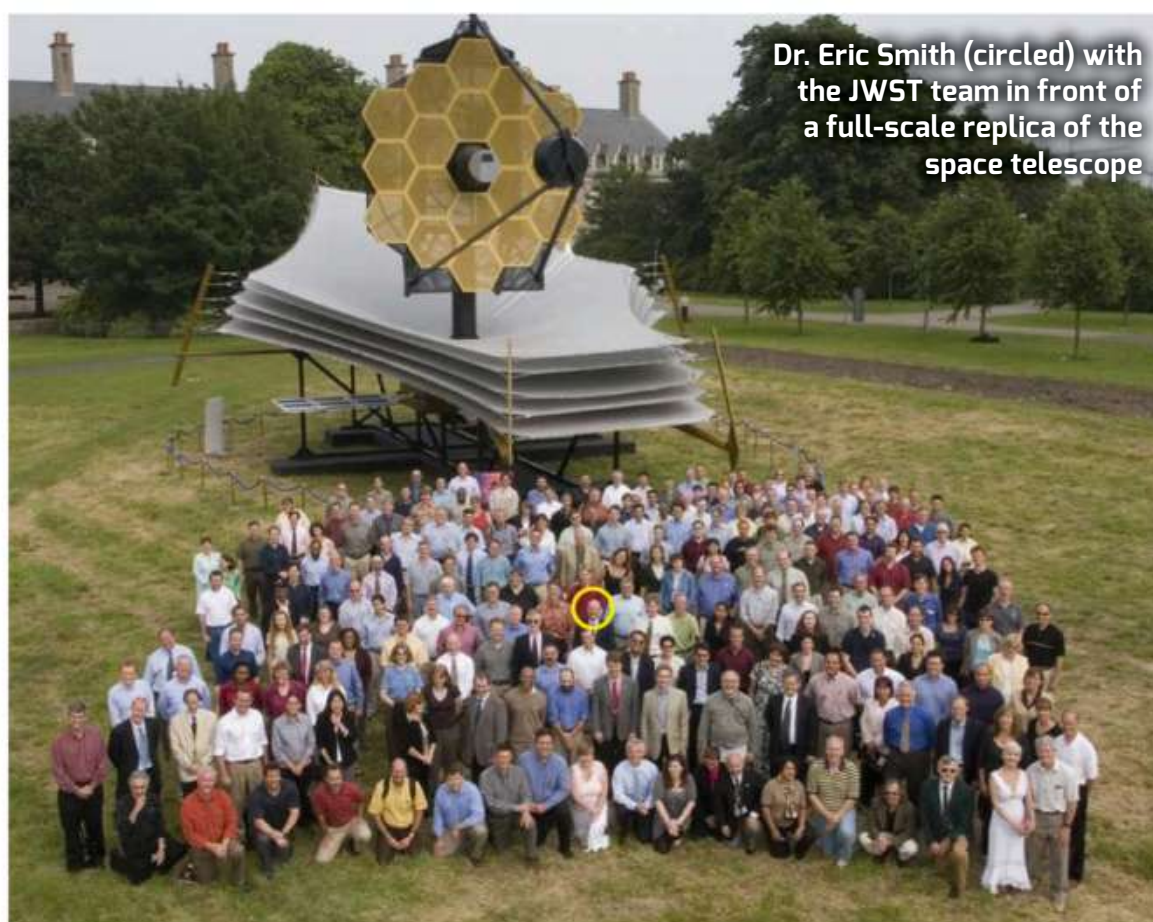
“Webb often gets called the replacement for Hubble, but we prefer to call it a successor,”

said Eric Smith, Webb’s program scientist at NASA Headquarters. “Its science goals were motivated by results from Hubble. More distant objects are more highly redshifted; thus, observations of these distant objects require an infrared telescope.”

This capability, together with its large mirror and distant orbit, sets it apart from Hubble. And, unlike Hubble, visible and ultraviolet imaging never really entered its remit. “We looked at how far into the visible we could optimise Webb,” said Smith. “Keeping in mind Webb sensitivity reaches down to the very red part of the visible spectrum, a very large ground-based telescope would be used by astronomers to answer questions best addressed with visible light.”

Webb’s complexity demands high systems reliability. “It employs an extensive seven-year integration and test program to exercise the system and uncover any issues prior to launch,” said Smith. “Hubble did not have a final system test – which could have caught the problem in the fabrication of the primary mirror – because it was deemed too complex and expensive. Webb is not designed for servicing; thus Webb must be done right.”

Whenever we think of telescopes, we think of them requiring tubes to ‘baffle’ stray light away from their optics.



Dr. Eric Smith (circled) with the JWST team in front of a full-scale replica of the space telescope

“Webb is not designed for servicing; thus Webb must be done right”

But Webb’s Three-Mirror Anastigmat (TMA) ‘naked telescope’ has no tube. This minimises the mass of baffling to accommodate more scientific instrumentation, blocking stray light with its sunshield and keeping infrared stray-light sources – the Sun, Earth and Moon – in one part of the sky.

“Previous infrared telescopes used a two-mirror conic design, which were only corrected for spherical and coma aberrations,” said Smith. “As such, the image quality over larger fields-of-view suffers since astigmatism isn’t corrected in the telescope design. Webb was chosen to be a TMA so that

it could have good image quality of the larger field-of-view encompassing the four instruments, which could not be achieved with a two-mirror design. A secondary advantage is that a fine-steering mirror can be placed at the exit pupil to help image stability during science exposures.”

And is its \$10 billion price-tag worth it? “History shows that building a one-of-a-kind instrument is challenging,” said Smith. “But the capabilities that Webb has can’t be matched by any planned or existing facilities, making them uniquely valuable, addressing important questions in astrophysics.”



BBC

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